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Review of Facility Technology Options and Their Development Status

by
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This report reviews the status of new energy technologies which are potentially relevant to the Army's needs. It covers technologies having both short- and long-term potential that are being developed by various Government agencies and private firms. For each technology, this report:

- Describes the technology
- Summarizes its status
- Identifies its commercial availability
- Explains the development programs and the funding organizations
- Describes its major cost and performance issues
- Describes the possible Army applications.

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FOREWORD

This work was completed for the U.S. Army Engineering and Housing Support Center (USEHSC), under project 4A162781AT45, "Energy and Energy Conservation"; Task 01, "Planning for Energy Efficiency"; Work Unit 016, "Energy Technology Forecasting." Mr. B. Wasserman (CEHSC-FU) was the USEHSC Technical Monitor.

The work was performed under contract by Arthur D. Little, Inc., for the Energy Systems Division, U.S. Army Construction Engineering Research Laboratory (USACERL-ES). Dr. G. R. Williamson is Chief of ES. Mr. Larry Windingland was the USACERL Principal Investigator. The principal investigators for Arthur D. Little were Ms. Lisa Frantzis, Dr. Peter Teagan, and Mr. K. J. Leary.

COL Carl O. Magnell is Commander and Director of USACERL, and Dr. L. R. Shaffer is Technical Director.

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REVIEW OF FACILITY ENERGY TECHNOLOGY OPTIONS AND THEIR DEVELOPMENT STATUS

1 INTRODUCTION

Background

USACERL is carrying out a long range assessment, development, and demonstration program involving a wide range of new technologies, including energy modeling, heat recovery, renewable energy, energy management, conservation, controls, and fuel substitution. In all these categories there are technologies having both short term and longer term potential for reducing Army energy consumption. This makes it difficult to compare the various alternatives. Both the wide range of technologies and their varying states of development complicate the task of deciding how to distribute limited financial and manpower resources to build the most effective Army energy Research, Development, Test and Evaluation (RDT&E) program. The allocation of resources and the type of program will be influenced by the technologies' status and associated risk. Similar issues have been and are being faced by other Government and private organizations with wide ranging RDT&E programs.

These factors enter into a process of "technology forecasting" in which managers identify those technologies that show the best potential for meeting the objectives of the supporting organizations.

Objective

The objective of this research was to review the status of new and emerging energy technologies that have a strong potential to reduce energy consumption at Army installations. The review covers R&D efforts by government agencies and private industry, both in the United States and abroad.

Approach

This report identifies major RDT&E projects in place or planned by such organizations as the U.S. Department of Energy (DOE), Gas Research Institute (GRI), Electric Power Research Institute (EPRI), General Electric (GE), Federal laboratories, selected foreign organizations, and private industry. The specific technologies selected for discussion were chosen because they are appropriate for the energy loads and end use demands typical of Army facilities. In many cases, the technology may be nearly or already commercially available, but technical advances or efficiency improvements are expected to change its performance and thus its markets.

The technologies are grouped in chapters by type of application: heating, ventilating and air-conditioning (HVAC), onsite power, industrial systems, renewable energy, and miscellaneous. The discussion of each technology is divided into these sections:

- Description
- Technology Status/Commercial Availability

- Development Programs/Funding Organizations
- Major Cost/Performance Issues
- Possible Army Applications.

References are listed at the end of the report and are grouped by chapter and section.

Information on these topics was obtained by reviewing the literature, discussing them with key personnel in the supporting organizations, and interviewing professional R&D staff to get their evaluations of the technologies. The purpose of these reviews and discussions was to realistically assess the claims and goals of the technologies' proponents.

The technologies assessed fall into four categories:

1. Near Term Technologies -- These are either now or will probably be commercially available within 3 to 5 years.

2. Intermediate Term Technologies -- These are in an advanced development stage and may be available in 3 to 6 years.

3. Long Term Technologies -- These are in an R&D stage and, even if successful, will not be available in less than 6 years.

4. Long Term Leap-Ahead Technologies -- These show promise for potential Army application but are not yet in the R&D mainstream.

Mode of Technology Transfer

The information will be reviewed by Corps of Engineers National Energy Team (CENET) members and evaluated by USACERL principal investigators, team leaders, and management personnel. They will use it to develop a more comprehensive RDT&E program, possibly using these technologies, to enhance the return on investment of energy R&D products.

2 ENERGY RESEARCH PROGRAMS OF MAJOR U.S. ORGANIZATIONS

The level of funding and support for energy research provided by Government and industry organizations varies considerably depending on their objectives and philosophy. Table 1 shows that in addition to the foreign and U.S. industry R&D activities, a significant amount of R&D is supported by a few key U.S. organizations: GRI, EPRI, and DOE. The objectives of these organizations are briefly discussed below, to give the context of the development activites discussed later.

Gas Research Institute (GRI)

The GRI plans, manages, and develops financing for cooperative R&D programs in the supply, transport, storage, and end use of gaseous fuels, for the mutual benefit of the gas industry and its present and future customers. Its total planned 1987 contract budget for R&D was $158 million, of which $86 million is for end use projects. Its underlying objectives in selecting technologies for development are listed in Table 2, along with some of the technologies being explored to meet these objectives. GRI's focus has changed significantly over the last few years from an emphasis on improved, energy-efficient, end use equipment (prompted by perceptions of gas shortages) to an emphasis on expanding the use of gas into new and current markets (a trend prompted by perceptions of ample [even excess] gas supplies). The GRI and DOE often cofund technology developments; gas-fired Stirling engine heat pumps are one example. These two organizations, however, have fundamentally different objectives in funding such technologies, since DOE's objective is to reduce overall energy consumption on a national basis and GRI's objective is to increase gas use, particularly in the summer.

GRI's overall end use objective is to develop improved gas-using equipment that is more effective, meets environmental standards, and offers competitive consumer costs at equivalent or higher quality of service compared to other energy service options. Given this strategy, GRI's program now emphasizes:

- Cogeneration technologies suitable for residential, commercial, and industrial applications.
- Gas-fired heat pump technologies to maintain current heating markets and expand into cooling markets not now served by gas.
- Gas-fired air-conditioning (commercial) to expand gas sales overall and particularly during the summer months.
- "Smart house" technologies which provide flexibility for using gas in homes to flexibly serve a full range of HVAC, cooking, and air quality control functions.
- Improved appliances (stoves, clothes dryers, etc.) to maintain and expand gas industry market share.

Table 1

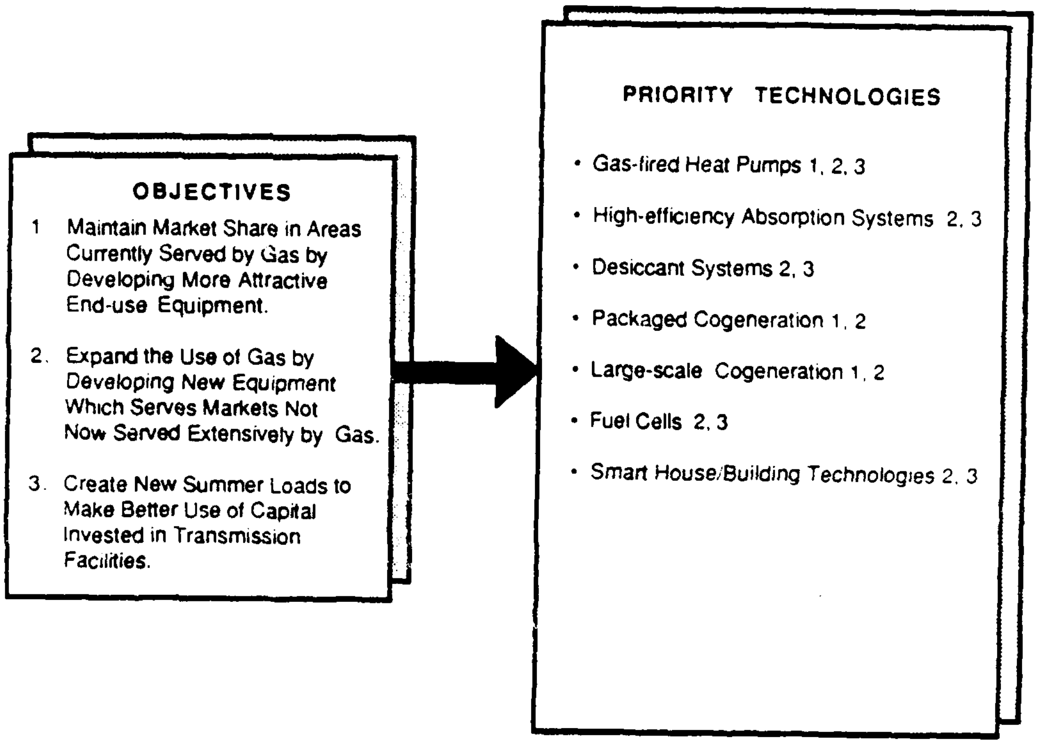
Technology Funding Priorities*

HVAC EQUIPMENT	GRI	EPRI	DOE	Japan/ Europe	Corp- orate	NYSE- RDA**
Variable speed heat pumps	-	2	2	1	1	-
Ground coupled heat pumps	-	1	3	3	-	2
Gas fired heat pumps (engine driven)	1	-	1	-	1	-
High efficiency absorption systems	1	-	1	1	2	-
Desiccant systems	1	-	3	-	3	-
Mixed refrigerants	-	2	2	-	-	-
Evaporative coolers	3	-	3	3	3	-
Cold storage systems (ice, chilled water)	3	1	3	3	3	2
Ventilation air heat recovery	3	3	-	3	3	-
ONSITE POWER						
Packaged cogeneration	1	-	3	2	2	3
Large-scale cogeneration	2	-	3	2	1	1
Coal-firing technologies	-	1	1	2	1	2
Fuel cells	1	1	1	2	1	2
High efficiency motors	-	2	3	3	2	-
INDUSTRIAL SYSTEMS						
Condensing heat exchangers	3	3	-	2	2	3
High temperature recuperators	3	-	2	2	2	1
Industrial heat pumps	3	3	2	3	3	2
RENEWABLE ENERGY SYSTEMS						
Photovoltaics	-	1	1	1	1	3
Solar water heating	3	3	2	2	3	-
Wind power systems	-	2	2	1	2	3
Passive solar building design	-	3	3	3	3	2
MISCELLANEOUS						
Insulation	-	-	3	3	3	-
High efficiency lighting	-	2	1	3	2	2
Smart house/buildings	2	2	-	3	1	-
Batteries	-	1	1	1	1	-
Daylighting technologies	-	-	2	1	2	3

*Ranking: 1--major thrust; 2--modest thrust; 3--minor activity.
**New York State Energy Research and Development Authority.

Table 2

GRI Objectives and Priority Technologies



Electric Power Research Institute (EPRI)

Generally, EPRI's mission is to lead and perform R&D to assist the electric utility industry give its customers energy services of the highest value. EPRI's objectives and technologies being explored to meet them are listed in Table 3.

The 1987 budget for EPRI's R&D activities totaled about $239 million, of which $23.1 million was in utilization and $163.3 was in generation. A major emphasis in 1987 was energy efficiency and load management, given many utilities' goals of least-cost planning and demand-side management. Technologies receiving major attention at EPRI include energy storage, atmospheric fluidized-bed combustion, fuel cells, batteries, compressed air storage, photovoltaics, improved heat pumps, and load management systems to reduce peak demands.

Department of Energy (DOE)

The general strategy and charter of the DOE have changed significantly over the last 6 years. In the late 1970's and early 1980's the DOE actively participated in the commercialization process by supporting market studies and demonstration programs. The current strategy emphasizes longer term R&D at the early development stages when the commercial risks are higher. Industry is expected to bear an increasing burden of the development costs (through cost sharing, etc.) as the technology gets closer to the

Table 3

EPRI Objectives and Priority Technologies

OBJECTIVES

1. Develop Improved Equipment to Increase and/or Maintain Market Share in Space Heating, Water Heating, and Individual Processes.
2. Develop Technologies That Reduce Peak Demands on Utilities (Especially During Summer Months).
3. Develop Technologies That Deliver Safe, Reliable and Environmentally Acceptable Electricity.

PRIORITY TECHNOLOGIES

- Variable Speed Heat Pumps 1, 2
- Ground Coupled Heat Pumps 1, 2
- Cold Storage Systems 2
- Mixed Refrigerants 1, 3
- Coal-fired Technologies 1, 3
- Fuel Cells 1, 2
- High-efficiency Motors 1, 2
- Photovoltaics 1, 2, 3
- Wind Power Systems 1, 3
- Batteries 2
- Smart House/Building Technologies 1, 2
- High-efficiency Lighting 2

commercialization stage. The interpretation of this general strategy is quite subjective and varies significantly between operating divisions of the agency. The DOE's general objectives and target technologies are listed in Table 4.

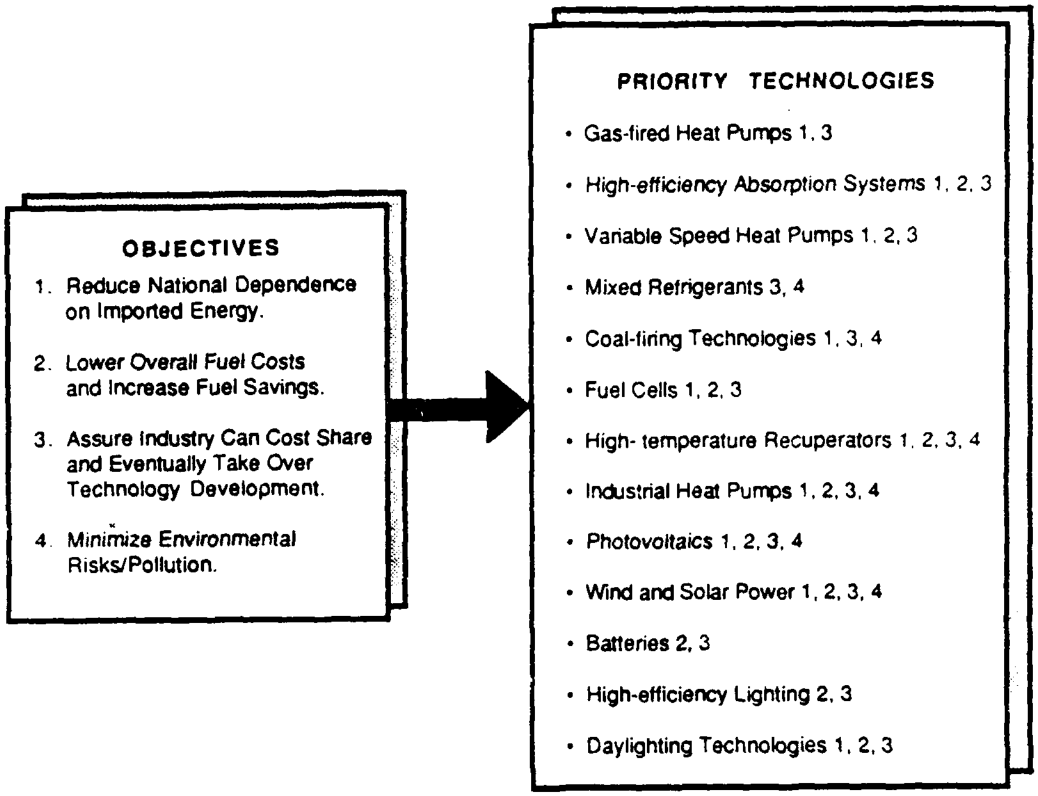
The current program planning tends to rely on the general knowledge gained in the early 1980's regarding what technology/applications are likely to have significant national impacts if successfully developed and commercialized. These plans usually do not attempt to quantify the impacts of technology developments.

There are two main divisions within DOE that conduct R&D on technologies relevant to the Army: Fossil Energy and Conservation and Renewable Energy. Fossil Energy has the primary responsibility for developing technologies that will increase domestic production of oil and gas or that will permit the nation to shift from oil and gas to more abundant coal and oil shale resources. Conservation and Renewable Energy primarily manages programs designed to increase the production of renewable energy and to improve energy efficiency in transportation, buildings, industrial and community systems and related processes. This includes support of high-risk, high-payoff R&D that would not otherwise be carried out by the private sector. The DOE's direction is influenced by national policy issues such as:

- The continuing objective to reduce the national dependence on imported energy with its security and balance of payment implications

Table 4

DOE Objectives and Priority Technologies



- The continuing objective to reduce the national dependence on imported energy with its security and balance of payment implications

- The potential for lowering overall fuel costs and increasing fuel savings over the longer term, thus increasing U.S. competitiveness and benefiting consumers.

Initially (late 1970's to early 1980's) the advanced fossil fuel technologies were economically rationalized based on their potential for competing directly with oil/gas, assuming rapidly escalating prices for these premium fuels. The programs are now, however, increasingly justified based on the noneconomic considerations indicated above. These programs are receiving major emphasis:

- Coal-fired diesel engines to provide more flexibility for coal use in smaller power systems.

- Advanced fluidized bed combustion systems to reduce air pollution problems and enhance flexibility for use in smaller facilities.

The total 1987 budget for Energy Conservation was about $430 million: $170 million for Renewable Energy, and $275 million for Fossil Energy. In addition to the $275 million, $400 million is allocated for a Clean Coal Demonstration Program. Oil and gas R&D in Fossil Energy currently only receive about 10 percent of the $275 million; coal receives 85 to 90 percent.

3 HEATING, VENTILATING AND AIR CONDITIONING

Variable Speed Heat Pumps

Technology Description

Microelectronics and solid state inverter technology has evolved to the point where it can be used to vary the operating speed of heat pumps so that system output closely matches building loads. This can result in a number of important advantages, including

- Higher efficiency levels (10 to 20 percent) on an annual basis
- "Soft start" of the motor compressor.

Technology Status/Commercial Availability

Inverter driven heat pumps are now a standard product in Japan for capacities of 1 to 3 tons.* Current annual sales exceed 80,000 units, compared to nearly zero just 4 years ago. Several U.S. manufacturers have developed initial products, but none are yet in wide commercial use. The Japanese experience indicates, however, that the technology is well developed and will probably gain a widespread market share over the next few years in the U.S. for low to moderate capacity (1 to 20 ton) equipment.

Development Programs/Funding Organizations

Support for variable speed heat pumps is being provided by both industry and government sources.

- Development in Japan is primarily by the manufacturers including Toshiba, Hitachi, Mitsubishi, Sanyo, and Daiken. Systems are available primarily in capacities from 0.5 to 3 tons, with emphasis on split systems (0.5 to 1.5 tons).
- Several U.S. companies have developed or are in the process of developing variable speed drive units. Carrier has recently introduced a central unit with a capacity of about 3 tons.
- EPRI is sponsoring a test program conducted by Honeywell and the University of Minnesota to assess performance of heat pumps under U.S. climatic conditions.
- DOE is planning a program to analytically and experimentally evaluate variable speed heat pump systems, emphasizing seasonal performance characteristics.

Major Cost/Performance Issues

The energy savings potential and improved comfort from variable speed heat pumps are reasonably well known. However, quantitative definitions of energy savings for different U.S. climatic regions and building types are still not available.

The cost premium for variable speed heat pumps in Japan is about 20 percent above that of a conventional unit. Improvements in inverter technology and larger production

*1 ton of cooling is equivalent to 12,000 Btu/hr.

volumes should reduce this premium over coming years. Payback periods on equipment based on energy savings will depend heavily on electric rate structures--particularly if demand charges are involved.

Possible Army Applications

Army facilities are using more air-conditioning in offices, athletic facilities, and living facilities--particularly in southern regions. Variable speed drive heat pumps can potentially lower operating costs and, possibly, lower capital costs of building HVAC systems in such facilities. The large size of air-conditioning loads could make this a major factor in the installation's electric energy consumption and in determining increasing demand charges.

The "soft start" capability of variable speed heat pumps also provides an advantage when they drive by onsite power systems, since current surges are eliminated.

Ground/Water-Coupled Heat Pumps

Technology Description

Both the capacity and efficiency of air-source heat pumps decrease in the heating mode as the outside temperature decreases. For example, at a temperature of 0 °F the coefficient of performance (COP) is only about 1 and capacity is only about 30 percent of standard Air-Conditioning and Refrigeration Institute (ARI) testing conditions (ambient temperature [TA] = 47 °F).* For this reason, air-source heat pumps are not very effective in the northern states.

Similarly, the performance of heat pumps operating in the air-conditioning mode decrease substantially as outside air temperatures increase over rated conditions (T = 80 °F).

One approach for both improving the performance of heat pumps and extending their range of applicability to more northern states is to "ground-couple" or "water-couple" the ambient condition heat exchanger (evaporator in the heating mode). In a ground-coupled heat pump, loops of pipe are buried either horizontally or vertically. For horizontal installation, 500 to 1000 ft of pipe is looped and buried 6 ft deep; for vertical installation, approximately 300 ft of pipe is buried as a single, vertical loop. The ground itself functions as a heat source (or sink) for the heat pump. In water-coupled heat pumps, either ground water or water from a nearby pond or river is pumped through a heat exchanger which interfaces with the heat pump.

The ground or water remains at a nearly constant temperature year round, acting as a low temperature storage media. Typically, ground temperatures (including groundwater) are in the 40 to 55 °F range even in northern areas and groundwater temperatures tend to remain constant between 47 and 50 °F. The performance of the heat pump is, therefore, independent of the ambient air condition, so it can function very effectively in both very cold and very hot ambient air.

*Metric conversion factors are given at the end of this report (p 92).

Technology Status/Commercial Availability

Both ground and water coupled heat pumps are now commercial technologies with several companies involved in their design and installation (Table 5). These systems are usually based on modest modifications of commercially available heat pumps used in commercial practice.

There has been a significant effort directed, however, at lowering installation costs by improving trenching techniques and ground-coupled piping arrangements.

Development Programs/Funding Organizations

Ground-coupled heat pumps have been viewed by the DOE and the electric utility industry as a promising option for improving the efficiency and extending the range of applicability of heat pump systems. Their activities in this field include:

- Development of packaged heat pump units specifically designed and optimized for ground-coupled operation (DOE program with Climate Master).
- Development of analytical techniques for designing ground-coupled heat exchangers and projecting energy savings (DOE and EPRI).
- Development of improved trenching techniques to lower the cost of ground-coupled heat exchangers.
- Participation in field test programs (DOE, EPRI, and several utilities such as Niagara Mohawk).
- Development of improved designs for direct-expansion, ground-coupled heat pumps (EPRI with DOE and utility participation).

Table 5

Ground/Water-Source Heat Pump Manufacturers

Company	System Sizes (BTUs)*
Florida HP Manufacturing	9,800 - 87,000
Friedrich Climate Master	24,000 - 61,000
Mammoth	28,000 - 62,000
Marvair Company	21,400 - 59,000
Water Furnace International	9,000 - 120,000

*High temperature cooling capacity.

The National Research Center in Canada has also been particularly active in supporting the development of improved ground-coupled heat pumps and of techniques to lower their installation costs. Their program includes defining soil properties, designing and testing heat exchangers, and conducting field demonstrations. Canadians have a particularly strong incentive for using ground-coupled heat pumps, given their relatively severe climate.

Major Cost/Performance Issues

The major cost in ground-coupled heat pumps is associated with trenching and laying down the heat exchanger. For water-source heat pumps the cost and reliability of access to the water source (well drilling, etc.) is the major cost. Therefore, the cost and performance of the ground/water-source heat pumps depend critically on soil conditions and/or water accessibility (Figure 1).

Under favorable conditions, the reported payback periods based on energy savings and lower heating equipment costs range from 2 to 5 years. Heating COPs for ground-coupled heat pumps range from 2.5 to 3.5. Cooling energy efficiency ratios (EERs) typically range from 10 to 15. Rating point heating COPs for water source heat pumps range from 3.0 to 4.0. Cooling EERs for water source typically range from 11 to 19 for reverse cycle systems and as high as 45 for direct cooling systems.

Possible Army Applications

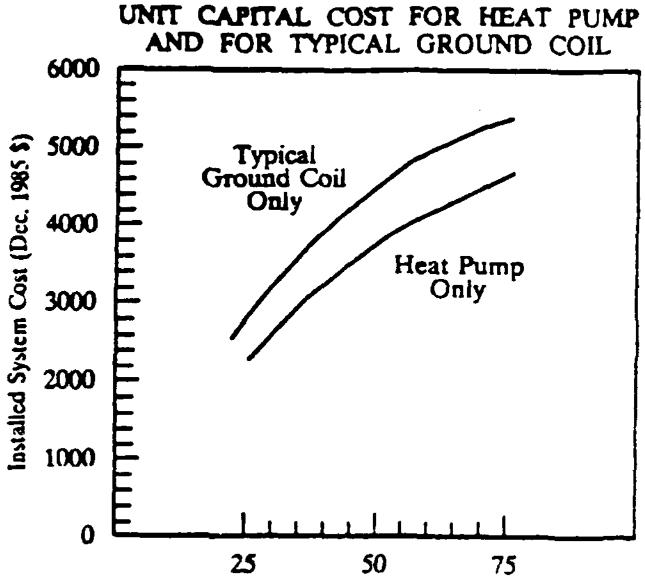
Ground/water coupled heat pumps could be widely applicable on Army installations for these reasons:

- Multiple systems could be installed at a base. This would greatly lower the costs of trenching since specialized equipment could be used more than once.
- Most Army bases have ample land near to buildings for trenching (installing piping systems).
- Once installed, the ground-coupled heat pump units are very reliable and have low operation and maintenance (O&M) costs.
- The steady load imposed by the heat pump systems (due to the steady source temperature) reduces demand charges for utility-purchased power and/or enhances the performance of onsite generated power systems.

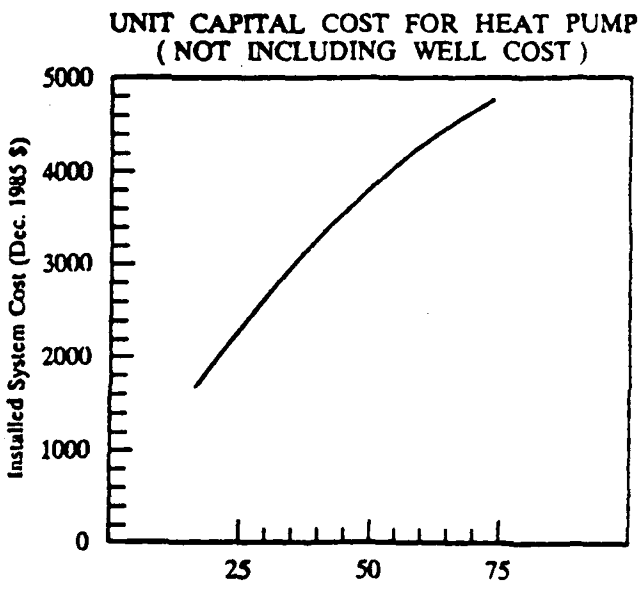
Gas-Fired, Engine-Driven Heat Pumps

Technology Description

An engine can be used to replace the electric motor of a conventional heat pump system. This way gas, oil, or other fossil fuels can be used to directly drive a heat pump system that delivers both heating and air-conditioning functions. This arrangement also uses the engines reject heat, further increasing system efficiency in the heating mode of operation. Such systems can achieve heating COPs of 1.5 to 2.0 and cooling COPs of 0.9 to 1.4 using current technology. Improvements in efficiency are expected as the result of ongoing technology development programs. Current practice uses reciprocating internal combustion (IC) engines. However, systems using Stirling engines, rotary IC engines, and turbine technology are under development.



Ground-Coupled Heat Pumps



Water Source Heat Pumps

Figure 1. **Cost characteristics for ground/water heat pumps.** Source: "TAG™ Technical Assessment Guide, Vol 2: Electricity End Use," EPRI P-4463-SR. Vol 2, Part 1 (Electric Power Research, September 1987).

Technology Status/Commercial Availability

Engine-driven heat pumps have been available in Japan and Europe (mainly Germany) for several years in commercial sizes (10 to 100 tons). Two major manufacturers include Tokyo Sanyo and Volkswagon. Several thousand systems are now operational.

There are currently no commercially available units in the United States. However, several gas utilities have imported Japanese units for demonstration purposes and several U.S. manufacturers are in the advanced development stage. It seems likely that gas-fired heat pumps (GHPs) will be commercially available within the next 2 to 3 years.

Development Programs/Funding Organizations

The development and commercialization of GHPs for residential and commercial applications has high priority in the natural gas industry. Their incentives are to maintain their market share in space heating and to create a summer gas load. The DOE also views GHPs as an important technology as a means for reducing overall energy consumption. Table 6 indicates the major development programs and the participating companies. As indicated, the U.S. companies emphasize residential applications due to the large potential impact of this sector on energy use. GRI has programs underway to develop an advanced residential GHP and a commercial heat pump. The target characteristics of each are given in Table 7.

Table 6

Gas-Fired, Engine-Driven Heat Pumps and Air-Conditioning: Industry Participants

Company	Application	Status
Mechanical Technology, Inc.*	Residential (3 tons)	Developmental
Thermo Electron Corp.	Commercial (150 tons)	Precommercial
Batelle/Briggs & Stratton	Residential (3 tons)	Developmental
Stirling Power Systems*	Commercial (15 tons)	Developmental
Tokyo Sanyo**	Commercial (10 - 30 tons)	Commercial
M.A.N.2***	Commercial (50 - 300 tons)	Commercial

*Uses Stirling engine drive; all others use reciprocating IC engine.
**Japanese manufacturer; several models are available in Japan and several thousand have been installed as of early 1987.
***German manufacturer; several hundred commercial-size units have been installed as of early 1987.

Table 7

GRI's Development Goals for GHPs

	Advanced Residential	Commercial (by 1990)
Cooling capacity at 95 °F	2-3 tons	10 tons
Heating capacity at 47 °F	60,000-90,000 Btu/hr	120,000 Btu/hr
Minimum heating seasonal performance factor (HSPF)	1.6	1.3
Minimum cooling seasonal performance factor (CSPF)	1.0	0.80
Maximum manufactured cost (1986 dollars)	$1700	$6000
Electrical parasitics	--	900 W
Service life	--	10-15 years

Major Cost/Performance Issues

GHP can provide both heating and cooling while saving up to one-half the natural gas now used by a conventional furnace or one-fourth the energy used by a high efficiency (90 percent) furnace. The GHP can be a cost effective alternative to electric cooling where the cooling load is significant and the electric-to-gas price difference is high. Currently, the initial cost of the GHP is approximately 25 percent higher than other space-conditioning options such as electric heat pumps, which is a major challenge facing the development and market penetration of this technology.

The primary barriers to widespread use in the United States are the relatively high O&M costs associated with available engines, relatively high noise levels, and high first costs. The development programs described above are all intended to mitigate these problem areas, particularly those associated with O&M. Recent progress in extending engine maintenance intervals to 1000 to 2000 hours (compared to 500 to 1000 hours in standard practice) indicates that this technology can achieve the reliability needed to serve U.S. markets, including those at military bases. In addition, GHPs can serve to reduce demand charges and energy consumption costs at Army bases.

Possible Army Applications

Army installations could be excellent candidates for the cost-effective use of GHPs. Their use could reduce gas or oil consumption in heating functions by 50 percent and reduce peak demands in the summer at installation with substantial air-conditioning loads. Also, the use of multiple units can facilitate O&M and provide a more secure

heating and cooling system. The systems could be used both in new facilities and for retrofits, possibly leading to widespread use.

High Efficiency Absorption Chillers

Technology Description

Gas-fired absorption chillers represent one class of thermally driven air-conditioning equipment. Unlike steam-driven absorption chilling, gas-fired equipment uses combustion products at temperatures on the order of 500 °F to produce the refrigeration effect. The advent of gas-fired chillers has opened up the commercial market to absorption technology, since steam-driven equipment was suitable primarily for process applications.

This section discusses the applications of gas-fired absorption systems in the 5- to 1,500-ton cooling range. The primary market for the chillers includes apartment buildings, small office complexes, and various institutional customers.

Technology Status/Commercial Availability

Direct-fired absorption equipment is produced mainly by three major manufacturers: Preway-Servel, Yazaki, and Hitachi. The leading manufacturers of steam-driven machines are Trane and Carrier.

Preway-Servel's equipment uses a single-effect, ammonia/water design. Its size ranges from 3 to 5 tons of cooling. Air-cooled condensers simplify the system design and are standard for equipment in this size range.

The Yazaki direct-fired absorption systems feature double-effect, medium capacity chillers (7.5 to 100 tons of cooling) and use a lithium bromide/water working fluid pair. These machines generally require cooling towers to dissipate reject condenser heat. Both heating and cooling operations are possible through the use of isolation valves. All Yazaki units use a two-setting power burner which results in heating efficiencies of 83 percent.

Hitachi units are marketed in the United States by Gas Energy, Inc., of Brooklyn, NY. Like Yazaki, Hitachi equipment uses a double-effect, lithium bromide/water cycle and ranges in capacity from 100 to 1,500 tons of cooling. Unlike the previous systems, however, Hitachi units can simultaneously deliver heat and chilled water, making them well suited for large office buildings.

Development Programs/Funding Organizations

The development of a cost effective absorption cooling system that yields a high cooling COP is a major thrust in GRI and DOE. The 1987 GRI funding level for R&D in this area has over $3 million, with funding being allocated at least through 1991. The other major R&D efforts are in the DOE and Japan. The two primary Japanese companies conducting much of the R&D are Yazaki and Hitachi, as discussed above. U.S. companies such as Phillips Enginering and Battelle Laboratories are also involved with R&D efforts for absorption chillers.

Major Cost/Performance Issues

Technical performance characteristics for typical absorption chillers are shown in Table 8.

According to manufacturer's literature from Preway-Servel, the cooling COP for a 5-ton machine at rated capacity is 0.48. The unit can also be operated in a heating mode by using the generator burner to provide heat to a hydronic circulating loop. Switchover between modes is accomplished by using a ball check valve which redirects water flow through the machine. The efficiency of the heating operation is 75 percent and is equivalent to a conventional gas-fired boiler. The modular nature of this system increases its capability to meet part-load conditions by cycling individual units off and on. Some absorption units have substantial efficiency decreases at partial load.

When used in the cooling mode, the Yazaki burner provides heat to the primary vapor generator and at design load results in a COP of 0.95. It should be noted that both heating and cooling performance (i.e., efficiency) is the same for all design loads. Also, representatives of Washington Gas Energy Systems (Springfield, VA) commented that part-load performance is excellent, with the COP and heating efficiency remaining constant down to 50 percent of design load.

The cooling COP for the Hitachi line is approximately 1 over a four-to-one load turndown. Heating efficiency is equivalent to conventional gas-fired boilers. It should be noted that although simultaneous heating and cooling are possible, performance trade-offs exist. Since less energy is available in the flue gas as a result of heating water, less refrigerant vapor will be volatilized to perform the cooling function.

The cost characteristics of the absorption systems discussed above are summarized in Table 9. There are distinct economies of scale for the large absorption systems.

Possible Army Applications

High efficiency absorption chillers can be used in many Army facilities that have a high cooling demand. Applications for these systems include troop barracks, large office buildings, processing plants, munitions facilities, and mess halls. Areas that currently use district heating or centralized boilers can level off annual loads by implementing high efficiency absorption systems to provide district cooling. Army bases that have a steam or gas heat source and a large air-conditioning load demand are potentially viable applications for this technology.

Desiccant Systems

Technology Description

Both solid and liquid desiccants can be used to absorb water from air streams. Table 10 indicates several of the material combinations used for this function. As such, desiccant systems can be used to dehumidify air for two main purposes:

- To provide dry air to storage facilities for better preservation of stored materials.
- To serve as part of the air-conditioning process, which involves both dehumidifying and cooling air.

The latter application is getting increased attention due to the pervasive use of air-conditioning in the U.S., particularly in the Southeast, where latent loads are often 40 to 50 percent of total air-conditioning loads. The desiccant unit can be used to dehumidify air, while a vapor compression unit is used to provide sensible cooling. Water vapor can also be added to deep dryed air (by the desiccant) to cool it by evaporative cooling. In all cases, the desiccant material absorbs large quantities of water. Heat must be supplied by solar, waste heat, or gas-fired sources to drive off the water (i.e., regenerate the desiccant material) so it can be reused. In this way, desiccant systems provide a means for switching air-conditioning loads from electricity to some other energy source.

Table 8

Technical Performance Parameters of Typical Fluid Absorption Chillers

Manufacturer	Equipment Type	Input Temp. (°F)	Evap.* Temp. (°F)	Cond.** Temp. (°F)	COP+
Yazaki					
• 50 ton	Double Effect Lithium Bromide/Water	350-600	45	90	0.95
• 100 ton	Double Effect Lithium Bromide/Water	350-600	45	90	0.95
Hitachi					
• 200 ton	Double Effect Lithium Bromide/Water	550-1500	44	85	1.0
• 500 ton	Double Effect Lithium Bromide/Water	550-1500	44	85	1.0
Servel					
• 5 ton	Single Effect Ammonia/Water	350-600	40	95++	0.48

*Refers to exit chilled water temperature.

**Refers to entering cooling water temperature.

+COP - Based on thermal input to the generator and cooling load requirements at design conditions.

++Refers to Air temperature entering condenser.

Table 9

Cost Characteristics of Absorption Systems

Manufacturer	Equipment Cost	Installed Cost ($ x 10^3)	O&M Cost ($/yr)	Comments
Yazaki				
20 ton	$18,700	*	100-200**	Potential cooling tower mods. Not included in installed cost.
30 ton	24,404	*	100-2000**	See above
100 ton	49,500	*	200**	--
Hitachi				
250 ton	115,000	144-230+	5,000++	Simultaneous heating and cooling possible
500 ton	193,000	240-386+	7.000	Simultaneous heating and cooling possible

*Estimated at $1400 o 1500/ton for all equipment.
**Based on service contracts offered by Washington Gas Company, Springfield, VA.
+Installation cost estimates range from 25 to 100 percent of equipment cost depending on retrofit or new installation.
++Estimates from Boston Area Hitachi Service Contractor.

Table 10

Common Desiccant Material Combinations

Solid Desiccants:

- Lithium chloride
- Silica gel
- Zeolites (molecular sieves)

Liquid Desiccants: (aqueous solutions)

- Lithium Chloride
- Calcium Chloride

Technology Status/Commercial Availability

Desiccant systems have been used for years to provide dry air for industrial processes (pharmaceuticals, film making, etc.) and storage facilities (e.g., "mothballed" naval ships). More recently several firms (Table 11) have introduced systems for using desiccants with air-conditioning systems. These range in capacities from 3 to 50 tons of latent heat removal and/or cooling capacity. Total sales of such units are still modest (<100), and the technology is only now entering into the early commercial stage for air-conditioning functions. However, the performance of field test units has verified the attributes of desiccant-based air-conditioning systems, and their commercialization over the next 5 years appears well assured.

By the mid 1990's GRI is expected to have a free-standing gas dehumidifier commercially available. The technology would use desiccants regenerated with gas heat to offer better moisture removal rates and lower life-cycle costs than electric dehumidifiers. These systems will have the added ability to remove airborne contaminants.

Development Programs/Funding Organizations

Desiccant technology is viewed as one of the most promising for developing viable, gas-fired air-conditioning systems. Consequently, this technology is receiving major

Table 11

Manufacturers: Desiccant Unit Systems

Company	Technology
Cargo Caire	Desiccant wheel, lithium chloride
Wing Company	Desiccant wheel
Kathabar	Liquid desiccant, lithium chloride
Seibu Giken*	Desiccant wheel, silica gel
Daiken Industries*	Desiccant wheel, lithium chloride
Thermo-Electron Corporation**	Desiccant wheel
American Solar King	Lithium chloride

*Japanese firms.
**Preproduction systems only, using heat wheels or liquid desiccant supplied by others.

attention from both manufacturers and the gas industry. GRI projects are at the forefront of gas industry efforts to develop desiccant-based cooling systems:

- A desiccant unit (using desiccant wheels) that is specifically geared to supermarkets and other applications having large latent loads.
- A 3-ton unit using solid desiccants for residential and light commercial applications.
- A 3-ton unit using liquid desiccants for residential and light commercial applications.
- Development of advanced desiccant materials.
- Development of analytical approaches for assessing latent heat loads on buildings.

The DOE also plans further support for development of desiccant cooling systems. The primary effort to date has been solar applications where desiccant materials are regenerated using solar-generated heat. This includes basic investigations of desiccant materials and the development of improved desiccant configurations (desiccant wheels, etc.). This work has been done primarily by the Solar Energy Research Institute (SERI).

Major Cost/Performance Issues

Desiccant-based cooling systems have only recently been introduced for commercial applications and most units would still be considered field test units. There is, therefore, only limited experience with which to assess long term performance and reliability characteristics.

The economics of such systems are becoming increasingly favorable in many applications as summer electricity rates and demand charges increase. Desiccant-based cooling systems use natural gas for desiccant regeneration, so they can significantly reduce summer electric loads.

Another potential advantage of desiccant-based systems is that the desiccant materials themselves tend to improve air quality by absorbing airborne pollutants. The degree of air cleaning is, however, still poorly quantified and is under active investigation by GRI and others.

Possible Army Applications

There is a wide range of possible applications within Army facilities:

- Maintaining acceptable humidity levels in storage and warehouse facilities, thereby maintaining the quality of goods and systems over long periods (particularly where sensitive electrical and mechanical equipment is involved).
- Humidity control in athletic and health facilities (swimming pools, etc.)
- General air-conditioning functions in office, residential, and assembly buildings commonly found on Army installations.
- Use of waste heat from onsite power systems.

Vapor Compression Cycles Using Mixed Refrigerants

Technology Description

Nonazeotropic refrigerant mixtures (solutions whose vapor/liquid composition changes with the concentration) offer certain theoretical advantages over pure refrigerants in vapor compression cycle performance. Attempts have been made to exploit two specific potential attributes: (1) the phase changes in the evaporator and condenser occur over a temperature range, providing the opportunity to design the heat exchangers to achieve lower thermodynamic irreversibilities in the heat exchange process; and (2) capacity modulation may be accomplished by partially separating the mixture components to change the fraction of the more volatile component in the circulating fluid.

Component separation requires both a means of storing refrigerant, since the total charge may be much larger (2 to 5 times) than in a conventional heat pump, and additional controls to achieve the desired separation. High performance also requires the presence of an interchanger between the evaporator and condenser to maximize subcooling.

Mixed refrigerants have been explored to find a substitute for pure refrigerants that are thought to contribute to ozone depletion (e.g., R12, R11, R113, and R114).

Technology Status/Commercial Availability

Interest in potential application of mixed refrigerants has peaked in the past 3 to 5 years. The major effort has been directed towards refrigeration systems (involving more than one evaporation stage) and residential heat pump systems. Because of the complexity of the technology and the behavior of nonazeotropic mixtures, the work has been largely theoretical, supplemented by some breadboard-type testing. These technical problems are being considered:

- Potential flammability resulting from preferential leaks of one of the mixture components
- Decreased heat transfer properties compared to pure components
- Methods of controlling the direction of refrigerant flow relative to air flow across the evaporator
- Optimum refrigerant mass flow control to adjust to changing conditions.

Currently at least one manufacturer of heat pumps (Tohiku Electric Power Company) uses a fixed mixture of R22 and R13B1 in residential heat pumps to boost heating capacity at low ambient temperatures. Another Japanese manufacturer (Daikin Industries) reports experiments with high temperature (100 °C water temperature) output in which both capacity and COP were significantly improved over a conventional heat pump that uses R114.

It is likely that most of the activity will remain in the research stage in the next 5 years. Interest may pick up in response if at some time the industry is to replace R12 and R114 due to environmental concerns. However, results to date do not indicate that the technology will become commercially viable on a significant scale.

Development Program/Funding Organization

Several European and American organizations are involved in this research, with particular interest in Europe due to their high heating requirements relative to air-conditioning. In the U.S. the DOE has sponsored programs with the National Bureau of Standards (NBS) to study transport properties of mixtures, with Arthur D. Little, Inc. to identify promising refrigerant mixtures and system configurations by analyzing heat pump heating and cooling applications, and with the University of Illinois to test refrigerant systems. EPRI has funded research to study fundamental properties of mixed refrigerants (Carrier Corp.) and to develop a detailed simulation model (NBS). Allied Corporation has carried out breadboard tests using various refrigerants; Du Pont Corporation has tested a modified heat pump using an R13B1-R152a mixture.

Major Cost/Performance Issues

Major cost and performance barriers for mixed refrigerants are capacity modulation and COP improvements. Currently, variable speed drives are more cost effective and efficient for capacity modulation.

Possible Army Application

The main applications for mixed refrigerants in Army facilities will most likely be those dictated by environmental concerns. Mixed refrigerants can be used in Army facilities when the capacity of a heat pump or air-conditioner needs to be tailored to a specific end use. Fluorocarbons are also becoming an increasing concern because of ozone depletion problems. Mixed refrigerant components that are benign can then be used to supplement fluorocarbons used in heat pumps and air-conditioners in Army facilities.

Evaporative Cooling

Technology Description

The evaporation of water can be used to cool air to temperatures within about 5 to 10 °F of its dewpoint. In many areas of the West and Southwest, dewpoints are typically 50 to 65 °F during the summer months. Thus a significant level of cooling can result from evaporative techniques. Even in the Midwest and Northeast, summer dewpoints average around 65 °F. In principle, therefore, evaporative cooling can be considered for part of an air-conditioning function in all but very humid regions of the Southeast.

There are two basic approaches to using evaporative cooling for air-conditioning functions (Figure 2). In the direct method, water is injected into the incoming air stream. As it evaporates the dry bulb temperature of the air decreases. Unfortunately, the humidity of the air also increases, resulting in a constant-enthalpy process. Such systems have been used in arid regions for years and are often called "swamp coolers".

In the indirect method, evaporative cooling is used to cool a water source which in turn cools the surface of a heat exchanger. Air is passed over the cooled surface, which reduces its temperature without increasing its humidity. Such systems allow evaporative cooling systems to deliver cool and relatively dry air in many parts of the country. An additional popular arrangement is an indirect stage followed by a direct stage evaporative system.

Technology Status/Commercial Availability

Evaporative cooling systems have been available for years, particularly in dry areas of the Southwest, where they are very effective. However, a growing number of more effective systems are now being offered by the manufacturers listed in Table 12. Most of these companies manufacture/install both direct and indirect evaporative cooling systems depending on location and application. In dry, arid regions, manufacturers project that evaporative coolers can satisfy the total air-conditioning load in many

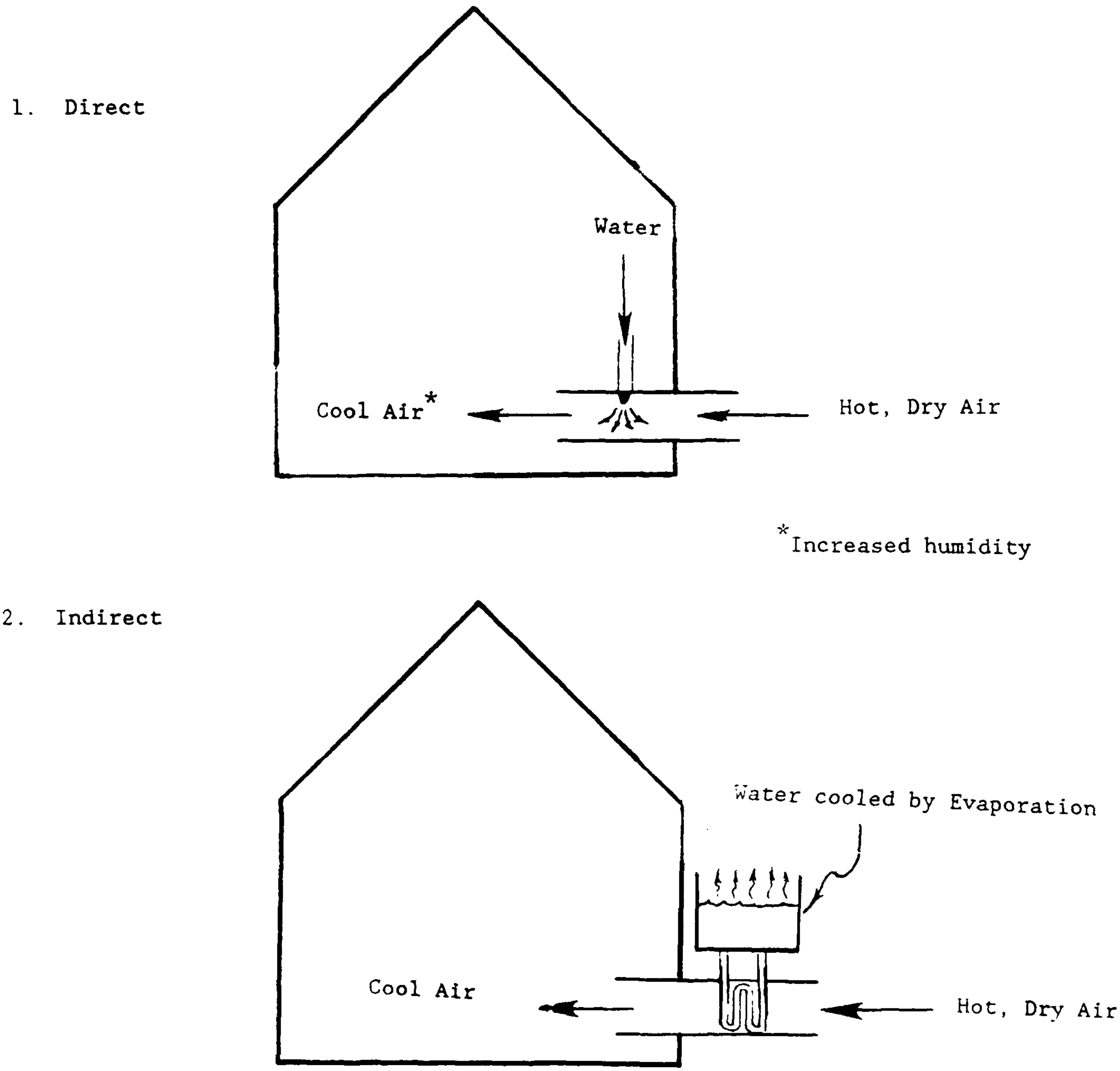


Figure 2. Evaporative cooling technologies.

Table 12

List of Evaporative Cooling System Manufacturers

Company	Application
Arvin	Residential/Commercial
Goettl	Residential/Commercial
Williams Furnace	Residential/Commercial
Lennox Industries	Residential
Dunham-Bush	Commercial
Photocomm Inc.	Commercial
American Air Filter	Commercial
Baltimore Air Coil	Commercial
Cargo Caire	Commercial
Niagara Blower	Commercial

Source: *Heating and Refrigeration News*, 1987 Directory Issue.

applications. In temperate areas evaporative coolers are often used in parallel with mechanical cooling systems to lower overall air-conditioning costs.

Development Programs/Funding Organizations

Some work was supported by DOE in the early 1980's as part of the renewable energy programs, since evaporative cooling takes advantage of natural processes. More recent developments, however, have been undertaken by equipment manufacturers.

Major Cost/Performance Issues

Evaporative cooler performance is quite sensitive to local climate and application requirements. There is a tendency, even in relatively dry areas, for such systems to deliver cool but relatively humid air. There could be periods during the year when the air is excessively humid, leading to extremely uncomfortable conditions for humans, or other humidity related problems such as mildew. These are reduced if evaporative cooling systems are used in conjunction with mechanical cooling, which can be operated to reduce humidity levels (low air flows, low evaporator temperatures).

Other practical issues affecting O&M in some areas is the buildup of scale or deposits if the water has a high mineral content. This could require frequent cleaning and, in some cases, cause corrosion of heat transfer surfaces.

With increasing costs of electric power, evaporative cooling is becoming a more attractive option for achieving space cooling. Payback periods are under 3 years in some applications, which is favorable compared to standard vapor compression technology.

Possible Army Applications

Many Army installations are in the West, where climatic conditions favor the use of evaporative cooling (either in standalone systems or in parallel with vapor compression systems) to lower energy costs. Using evaporative cooling to reduce the temperature of ventilation air in larger, high use facilities might be attractive in hot areas, particularly if ventilation loads have increased as a result of changing air quality standards.

Cold Storage Systems

Technology Description

In recent years, systems engineers have been forced to seek unique approachs to HVAC design in an effort to reduce peak load energy consumption. Cold storage is one method that has been well publicized. Thermal storage for cooling is now recognized as one answer to the increasing costs of operating today's air-conditioning systems. In this method, cooling capacity is generated and stored during electrical offpeak periods, then used during peak periods. This reduces maximum system peak electrical demand and takes advantage of lower, offpeak utility rates. The two most common forms of cold thermal storage are chilled water tanks and ice bank systems.

Both storage mediums operate on a similar principle. When the cooling load reaches a minimal level, typically at night, the refrigeration system operates to cool the storage medium. This process is typically achieved by circulating a cold refrigerant solution (such as water and glycol, freon, or ammonia), from a standard packaged air-conditioner chiller, through a coil which is submerged in the storage tank, to extract heat until the entire storage medium is at the desired temperature. This temperature is typically 26 °F for ice bank storage systems, and 44 to 45 °F for chilled water systems.

When refrigerant is required for cooling, the chilled refrigerant pump is started, initiating refrigerant flow, and the building cooldown cycle begins. Warm return refrigerant from the building circulates through the storage tank coil and is cooled by the storage medium.

Technology Status/Commercial Availability

Currently, technology development seems to be leaning towards ice bank systems. They often use space more efficiently, have no temperature blending problems, are more controllable, and are at least as efficient thermally. Table 13 lists some major suppliers of cold storage units from 600 to 500,000 lbs of storage capacity. The focus now is on commercial and industrial systems, where the scale is larger and the possibility of savings is proportionally higher. However, residential cold storage systems should become an important air-conditioning alternative by 1990.

Development Programs/Funding Organizations

Through their Load Management program, EPRI is the primary organization financing research in cold storage. New York State Energy Research and Development

Table 13

Manufacturers of Ice Storage Units

Ice Storage Manufacturer	Ton-Hours of Refrigeration	Cooling Refrigeration	Capacity
Turbo Refrigeration Co.	625 - 25,000	7.5 - 300	10,050 - 402,000
Calmac Manufacturing Co.	4,000 - 13,500	48 - 162	64,320 - 217,080
Baltimore Air Coil Co.	7,000 - 79,000	84 - 948	112,560 - 1,270,320
Chester-Jensen Co.	1,000 - 100,000	12 -1,200	16,080 - 1,608,000
Sullair Thermal Systems Inc.	57,000 - 495,000	684 -5,940	916,560 - 7,959,600

*Assumes a return water temperature of 55 °F and a full storage operating mode with a 12-hour ice recharge cycle.

Authority (NYSERDA) is beginning to become involved, and private industry will follow the lead of companies like Calmac Manufacturing and Sullair Thermal Systems, who are financing extensive private development programs.

Major Costs/Performance Issues

There are several domestic manufacturers which produce a "packaged" ice storage system. Once installed, this unit can be regarded as an integral component of the total refrigeration-storage system. This differs from a chilled water system, in which a unit's size and configuration is unique to the application. Space availability, however, is still a barrier to the market potential of chilled water technology.

The total costs of an ice storage system includes the equipment (Figure 3), transportation, and installation costs. The equipment cost is highly contingent upon the unit size, and charge/discharge rates; therefore the costs stated in Table 14 should be viewed as general guidelines only. The transportation costs depend on shipping distance and will typically add 3 to 10 percent to the cost of the system. The cost of installation can then be estimated by assuming that the contractor's purchase price is 15 percent below the manufacturer's list price. This purchase price is marked up by 10 percent to cover the cost of installation, by 10 percent more for contractor overhead costs, and by 15 percent more for contractor profit. The overall economics of ice storage systems are very dependent on the high demand charges being imposed by utilities throughout the United States. These demand charges, along with the rebate programs being offered by many utilities for ice storage installations, make ice storage an economically attractive technology in many areas of the United States where peak loads need to be reduced.

Table 14

Ice Storage Unit Costs

Ice Storage Capacity (lbs of ice)	Equipment Cost* ($)	Installed Cost ($)	Equivalent Capacity (ton-hour)	Normalized Cost ($ per ton-hour)
5,000	4,800	6,680	60	111
10,000	9,480	13,200	120	110
50,000	44,400	61,800	600	103
100,000	81,600	113,500	1,200	95
200,000	135,600	188,700	2,400	79
300,000	172,800	240,500	3,600	67
400,000	204,000	283,900	4,800	59
500,000	223,800	311,400	6,000	52
600,000	237,600	330,600	7,200	46
700,000	260,400	362,300	8,400	43
800,000	292,800	407,400	9,600	42

*Contingent in unit size and charge/discharge rate (general guidelines only).

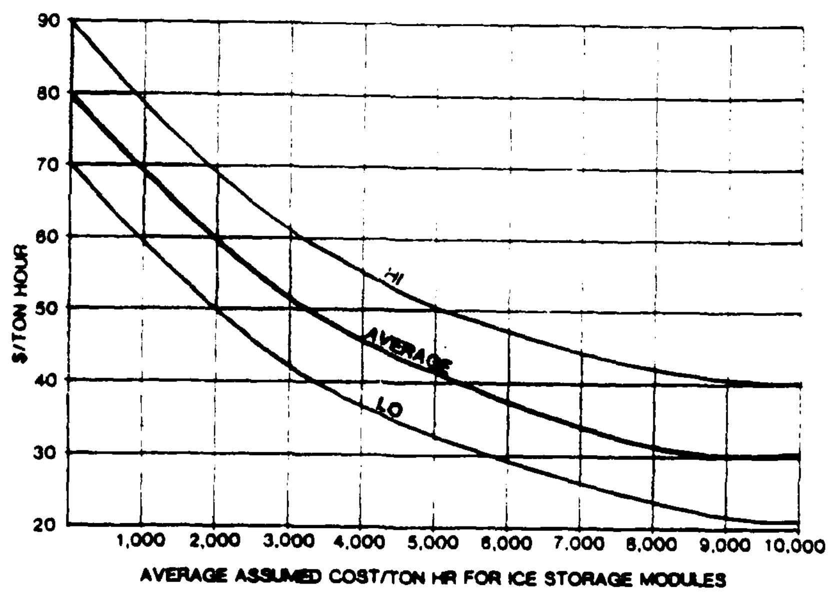


Figure 3. **Cost of ice storage equipment.** The cost is shown as a broad band because final price stabilization has yet to take place. Costs in this case are a ballpark estimate that includes heat rejection apparatus and electrical equipment, including tranformers.

Possible Army Applications

Army applications of cold storage would be similar to those in the civilian sector. Such systems could be used to reduce electric demand charges and capacity requirements of vapor compression equipment in all buildings which either have or are planned to have air-conditioning. The use of cold storage might be easier in many Army buildings than in civilian ones since land is often available nearby to buildings for placing outside cold storage volumes (if sufficient space is not available in the building itself).

Additional special applications may exist in Army facilities if and/or when onsite power systems (district heating, cogeneration, gas-fired chillers, etc.) are used to operate air-conditioning or large refrigeration systems. In such cases, cold storage could be used to reduce peak cooling demands and thereby reduce the required capacity and capital costs of the onsite power units.

Ventilation Air Heat Recovery

Technology Description

Many larger office buildings, health facilities, entertainment facilities, and dormitory-style living quarters use ventilation air to ensure proper air quality. The use of ventilation air is likely to increase as the result of the new American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standards, and as buildings otherwise become "tighter" as part of energy conservation efforts to reduce infiltration losses. The trend toward very tight construction has resulted in positive ventilation systems being used even on residential construction. The heating and cooling of needed ventilation air can represent 20 to 40 percent of the total load on many buildings--a number which is likely to increase as the result of the trends mentioned.

One approach for dramatically reducing ventilation air heating/cooling loads is to use ventilation air heat recovery systems. In such systems energy is exchanged between the exhaust air stream and the incoming ambient air used for ventilation. Several different types of heat exchangers can be used for this function, including plate-fin units, heat pipe units, and heat wheels. When heat wheels are used, the material can be coated with a water-absorbing media (desiccant) that transfers latent heat between the exhaust air and ventilation air while removing excess moisture--an attribute which is particularly important in reducing air-conditioning loads in humid areas. When appropriately designed, ventilation air heat recovery systems can reduce heating/cooling loads for ventilation air by 70 to 80 percent.

Technology Status/Commercial Availability

The primary drawback to ventilation air heat recovery units is that they require air to be exhausted from the building at a central location that is adjacent to the ventilating air intake (since exhaust air and ventilation air streams must exchange heat). In most buildings exhaust air flows through distributed vents, windows, leaks, etc., and no provisions are made for returning exhaust air to a central vent. In such buildings return air ducts would have to be installed. This might be an excessively costly undertaking in some buildings.

Ventilation air heat recovery systems are commercially available from the manufacturers listed in Table 15. These systems are suitable for residential and large commercial applications.

Table 15

Companies Offering Ventilation Air Heat Recovery Units

Company	Technology
Airesearch	Plate Fin
Aston*	Plate Fin
Astna*	Plate Fin
Des Champs Laboratories, Inc.	Plate Fin
Wing Company	Heat Wheel
ACS Hoval	Plate Fin
Q-Dot	Heat Pipe
Environmental Air Ltd.*	Heat Pipe

*Canadian companies: These systems are particularly cost effective in cold climates, leading to high level of use in Canada.

Development Programs/Funding Organizations

Ventilation air heat recovery systems are already in fairly widespread commercial practice. Most efforts to improve system performance are being undertaken by the manufacturers involved, with little outside support. Technical trends include:

- Improved enthalpy wheels using new materials and processes to enhance moisture removal capabilities. Japanese manufacturers are particularly active in this area.
- Improved heat exchanger design/manufacturing processes to result in higher effectiveness, lower cost, and more compact configurations.

Major Cost/Performance Issues

The use of ventilation air heat recovery units requires a central duct for ventilation air intake and one for exhaust air; these two ducts must be close together. When these conditions exist, the cost of installing ventilation air heat recovery units can be recovered in less than 3 years. However, in many buildings there is no return air duct system. Air essentially exhausts through distributed vents and other openings in the building (windows, etc.). In such cases additional ducts would have to be added to the building to return air so energy could be transferred to the incoming air stream. This installation can be quite costly and would restrict retrofit applications where such return ducts are not already in place.

Possible Army Applications

The Army will probably be increasing the use of ventilation air in its base facilities to improve air quality, as done in the civilian sector. This trend will affect the large number of eating, living, health, and entertainment facilities which exist at larger

installations. It is likely, therefore, that ventilation air heat recovery systems could be used effectively for a large number of Army buildings to reduce both heating and air-conditioning loads. Their use would be most attractive both in northern areas, where ventilation loads could significantly increase already large space heating loads, and in southern areas, where increasing use of air-conditioning is rapidly increasing electric power consumption and demand charges.

4 ONSITE POWER

Packaged Cogeneration

Technology Description

Larger (500+ kW) cogeneration systems are generally designed for a specific installation and assembled onsite using standard subsystems (engines, generators, controls) from a variety of suppliers. Packaged cogeneration systems, by contrast, are engineered modules which are factory assembled to be used either singly or in multiples for a wide range of applications. This approach has several advantages:

- Standardized, modular packages can be developed which eliminate the site-specific engineering and system design costs often associated with larger applications.
- The potential market (in number of units) is much larger for small modules than for custom-engineered larger systems. This could result in economies of manufacturing scale which could overcome inherent economies of size in individual components.
- Many applications over 30 kW might be better served by using multiples of smaller modules rather than a single larger unit, to:
    - Reduce vulnerability to increases in utility demand charges, since it is unlikely that more than one unit would go down at the same time (i.e., only a fraction of generating capacity would be lost with the loss of a single module).
    - Allow capacity to be increased incrementally as needs grow and users become more comfortable with the systems.
    - Better follow variable load conditions by allowing single units to be turned off.
    - Improve ease of transportation and installation, possibly reducing installation costs and improving siting flexibility within buildings.
- The development of standard modules to allow easy replacement for overhaul or repair. This, in turn, reduces costly site maintenance procedures.

Technology Status/Commercial Availability

Table 16 lists the major suppliers of packaged cogeneration units, and Tables 17 and 18 give the characteristics of several units on the market. Over 2,000 units with capacities of 10 to 150 kW have been installed in the United States and Europe over the last 5 years. Early development was primarily in Europe, represented by the Fiat Totem unit (15 kW). The largest supplier in the United States is currently Tecogen (60 kW), which has been installing units for about 3 years. The number of participants is now growing as the reliability potential of smaller units is demonstrated and as increasing utility demand charges enhance the economics of cogeneration for smaller uses.

Table 16

Major Packaged Cogeneration Suppliers

Company	Location	Size, kW
Empire Generator Corp.	Germantown, WI	20 and 42.5-250
Engenco, Inc.	Midvale, UT	16-25 and 125
Packaged Cogeneration Systems, Inc.	Thousand Oaks, CA	12-20
Teledyne Total Power	Memphis, TN	11.5-22
Thermex Power Products Corp.	Anaheim, CA	10.5
Micro Cogen Systems, Inc.	Irvine, CA	20
Van Weld	Albuquerque, NM	6.5
American M.A.N. Corp.	New York, NY	47-400
Arthur G. Dietrich Co., Inc	Cudahy, WI	300-515
Cogenic Energy Systems, Inc.	New York, NY	100-450
Hawthorne Engine Systems	San Diego, CA	65-600
Intellicon, Inc.	San Diego, CA	65
International Cogeneration Corp., Inc.	Philadelphia, PA	37-75
Martin Cogeneration Systems	Topeka, KS	100-500
Solar Turbines Incorporated	San Diego, CA	800
Stewart & Stevenson Services, Inc.	Houston, TX	515
Tecogen, Inc.	Waltham, MA	60-600
Waukesha Engine Service Center, Inc.	Compton, CA	45-500
Waukesha Power Systems	Waukesha, WI	30-375

Source: *Gas Research Institute Digest*, Spring 1987.

Table 17

Characteristics of Cogeneration Systems Using Reciprocating Engines

Manufacturer	Model/ Size	Prime Mover/ Fuel	Comments
American M.A.N. Corporation 50 Broadway, 18th Floor New York, N.Y. 10004	E 2566 E-A/ 85 kW D 2566 ME-A/ 103 kW E 2542 E-A/ 155 kW D 2542 ME-A/ 170 kW L 20/27 Series/375 kW and 470 kW	Spark/Natural Gas Diesel Spark/Natural Gas Diesel Spark/Natural Gas	All models are currently available and have been used in Europe for some time.
Brooklyn Union Gas 166 Montague St. 166 Brooklyn, NY 11201	TOTEM®/15 kW	Fiat 903cc Engine/Natural Gas, LPG, Biogas	Currently undergoing field tests; commercial introduction scheduled for late 1986; target cost is $1,500/kW installed; other sizes may be available; there are currently over 1,800 TOTEM® units in Europe.
Cogenic Energy Systems, Inc. 127 E. 64th St. New York, New York 10021	M-100/ 100 kW	Caterpillar 3306G/ Natural Gas	M-100 equipment cost $105,000. M-450 cost $400,000; about 50 units sold as of May, 1985. Units also available with Hitachi absorption chillers. Introduced in 1982.
Empire Generator Corporation PO Box 3099 Germantown, WI 53022	700 NKR-8E/ 70 kW and 1200 NKR-8E 120 kW 2100 DKR-8E/ 210 kW 3200 DKR-8E/ 320 kW	Various manufacturers/ Natural Gas Various manufacturers/ Natural Gas	Empire has the capability to produce other models and use other fuels. A 200 kW unit costs about $50,000, uninstalled; a 375 kW unit costs about $60,000, equipment only. Packaged line introduced in 1985.
Engenco Incorporated PO Box 400 Midvale, UT 80447	318 IPG/16 kW 325 IPG/25 kW 6125 IPG/125 kW	Lister Co./Propane	Engenco specializes in propane powered engines. Other models are available. The 25 kW unit lists for $22,000 and the 125 kW at $67,000. Packaged units introduced in 1985.
Martin Cogeneration Systems Division of Martin Tractor PO Box 1698 1637 S.W. 42nd Topeka, KS 66601	Series 1000; NA-HCR/100 kW NA-HCR/230 kW Series 2000; NA-HCR/350 kW NA-HCR/460 kW	Caterpillar G3306/ Natural Gas Caterpillar G379/ Natural Gas Caterpillar G398/ Natural Gas Caterpillar G399/ Natural Gas	Martin has other models available and diesel units are also available. Packaged line introduced in 1982.
Re Energy Systems, Inc. 637 West Baltimore Pike PO Box 1757 Media, PA 19063	TEPP™ Series; NG 20/20 kW NG 55/55 kW NG 75/75 kW NG 100/100 kW NG 200/200 kW	Natural Gas	Similar size units available using diesel fuel #2 and propane/LPG. TEPP™ stands for Total Energy Power Plant. First unit installed in 1981.
Thermo Electron Corporation 101 First Ave. PO Box 459 Walthan, MA 02254	Tecogen™/60 kW	Crusader Engine/ Natural Gas	Modular up to 180 kW. Installed cost about $60,000 to $70,000. Introduced in 1983.
Waukesha Power Systems Division of Dresser Industries Inc. 1220 S. Prairie Ave. Waukesha, WI 53187	VRG 330/45 kW F817/75 kW F1197/115 kW	Various Waukesha Engines/Natural Gas	Packaged units introduced in 1984.

Source: "Alternative Source of Energy," ISSN-0146-1001 (Alternative Sources of Energy, Inc., 1986).

Table 18

Characteristics of Cogeneration Systems Using Gas Turbines

Manufacturer	Model/ Size	Status	Packagers	Comments
Allison Gas Turbine Division of General Motors Corporation 2410 Exec. Dr. Indianapolis, IN 46241	Series 250-K/ 200 kW and 400 kW	Under Evaluation by Allison for cogeneration potential.		Adaptation of Series 250-K helicopter engines, cost target $1,000/kW; 60 to 80 psig steam demonstration system late 1985
The Garrett Corporation PO Box 92248 Los Angeles, CA 90009	IE 831-800/ 515 kW	In production.	Stewart & Stevenson Gas Turbine Products, Houston, TX	The 831-800 is a simple cycle, heavy duty industrial engine
	GT601/ 500 kW	Prototypes have been made. Under evaluation by Garrett for cogeneration potential.		Cogeneration considerations delayed until the GT601 is in production for military vehicles thereby providing a production base for volume manufacture
	AES/ 50kW	Under design. First tests in 1986.		Advanced Energy System (AES) cost target is $1,000/kW 34% electrical efficiency with initial units, 41% when ceramics are introduced.
Kawasaki Heavy Industries, LTD 1-1 Kawasaki-CHO Akashi 673 Tokyo, Japan Telex: 5628951	GP250/ 200 kW, Gp500/ 400 kW	In production.	Cullen Power Products, Inc., Hawthorne, CA; Turbo Systems International Lathan, NY; Valley GM Power Products, City of Industry, CA	Kawasaki does not manufacture packaged small scale cogeneration sets but Kawasaki's U.S. distributors do

Source: "Alternative Source of Energy," ISSN-0146-1001 (Alternative Sources of Energy, Inc., 1986).

Packaged cogeneration units are commercially available in capacities from 10 to 150 kW. The range of packaged units will certainly increase to several hundred kilowatts on the high end and be lowered to 3 to 5 kW on the low end to serve residential applications. The latter technology in a practical form is not likely for another five years. Of particular importance, the range and quality of units in the 10 to 150 kW range will continue to increase as this business becomes better established over the next 5 years.

Development Programs/Funding Organizations

Industry has provided primary resources for the development of packaged cogeneration units. In the United States the gas industry is a major supporter of cogeneration technology. More recently GRI has been providing direct financial support for the development of improved units by:

- Sponsoring a study to assess the technical/cost requirements of packaged cogeneration units to establish large markets in the 1 to 30 kW capacity range.

- Undertaking endurance and performance testing of six reciprocating IC engines showing promise for use in cogeneration applications.

- Supporting projects for developing advanced packaged cogeneration units. Funded projects show potential for meeting specific cost/performance goals.

GRI and DOE's advanced engine development projects would be directly applicable to cogeneration applications. These include:

- Free piston stirling engines, particularly in smaller capacity ranges (1 to 5 kW)
- Rotary IC engines (5 to 100 kW)
- Small recuperated gas turbines (50 to 200 kW)
- Free piston IC engines (5 to 50 kW).

Major Cost/Performance Issues

Particularly in sizes above 15 kW, well designed packaged cogeneration units have demonstrated favorable economics based on energy and demand charge savings. To increase their commercial acceptance, this technology can be improved by:

- Reducing O&M costs by extending the periods between routine maintenance and major engine overhauls
- Establishing reliable O&M networks for maintenance and repair
- Developing lower-cost electric utility grid interconnect technologies and procedures (for units below 15 kW capacity)
- Developing remote diagnostic techniques to sense when units require servicing.

Steady progress is being made on all these issues, which should ensure an expanding range and cost effective applications.

Possible Army Applications

Army facilities are ideal applications for packaged cogeneration systems.

- A large number of modules can be readily implemented in a small area, minimizing O&M costs.
- There are trained maintenance staff available to support the routine operation procedures (oil changes, etc.).
- Many installations have a mix of building types which are good candidates for packaged cogeneration (dormitories, gymnasiums, mess hall facilities, etc.).

Large-Scale Cogeneration

Technology Description

These types of large-scale cogeneration systems have been installed in the United States: boiler/steam turbine systems, gas turbine generators, and diesel generators. The systems differ primarily in these areas:

- Initial capital investment requirements ($/kWh)
- Thermal-to-electric production ratio
- Quality (temperature/pressure) of thermal energy produced
- Type of fuels required
- Overall efficiency.

In the industrial sector--the primary market for large-scale systems--the largest proportion of units have used steam turbines, followed by gas turbines, and a relatively small fraction of the large-scale units have used diesel generators.

Large-scale cogeneration systems (> 5 MW) are generally designed for a specific installation and constructed onsite. Systems usually use standard subsystems from various suppliers, but substantial onsite fabrication and/or erection is often required. Fabrication requirements vary by size and type of technology. Gas turbine or diesel systems are often skid mounted, and installation requirements are usually minimal, other than the necessary structural supports. Construction times can be less than 1 year in some cases. By contrast, a large steam turbine system has substantial fabrication/ erection requirements, often requiring 3 to 5 years for construction when solid fuel-fired boilers are used.

This technology has several advantages over smaller packaged cogeneration units:

- There are certain capital cost economies of scale with larger units, thus unit costs ($/kWh or $/MBtu) can be substantially lower than those associated with smaller units.
- There are certain efficiency advantages associated with larger units (e.g., due to increased mechanical efficiency, higher temperature or pressure capability, etc.).
- Larger units can economically incorporate technologies which are uneconomic in smaller units (e.g., pulverized coal firing, multiple extraction points on a steam turbine).
- Although multiple units can be (and are) installed, the tendency is to use fewer, but larger, units. For example, two 50 percent capacity stoker boilers cost about 10 percent more than a single 100 percent capacity boiler.

Technology Status/Commercial Availability

Cogeneration systems were first introduced in the United States at the turn of the century. The technology for topping cycles is fully developed and available from equipment vendors and engineering firms, as well as firms specializing in third-party development of cogeneration systems. Systems as large as several hundred megawatts have been installed. However, improvement of individual components continues. An example is the recent introduction of fluid bed boilers in steam topping systems to achieve fuel flexibility and reduce the cost of air pollution control.

Development Programs/Funding Organizations

Funding sources vary for individual component development, but current evolutionary development efforts are primarily industry-supported (Table 19). EPRI, GRI, and DOE all have funded various projects in the past, but current funding is limited, given the developed status of the technology.

Major Cost/Performance Issues

Cogeneration systems have demonstrated extremely attractive economics when compared with separate thermal and electric delivery systems. Key components in determining economic viability include the fuel type available and its cost, revenue from excess power sold to a utility (at the utility's avoided cost), plant operation (hours/yr) at average load conditions, plant thermal/electric load requirements, and annual operating hours.

A key cost/performance issue is selecting an optimum design for a given situation. Given the many variables which influence the design and performance of a cogeneration system, rules of thumb often do not apply, and a more thorough design optimization approach is required.

Possible Army Applications

Larger Army installations can be attractive applications for large-scale cogeneration. A key decision is whether to use a single, central installation or to install numerous smaller distributed "packaged cogeneration" systems. Electricity produced by large systems is sold to a local utility; this revenue reduces steam prices to below those available from standalone boilers.

Coal-Fired Technologies

Technology Descriptions

The major commercial coal-fired power technologies are stoker and pulverized coal firing. These technologies have been developed over many decades and are considered mature technologies. Recently, the increased emphasis on coal for energy independence (coal is an abundant resource in the United States) and on environmental protection (particularly acid rain) has fostered the development of:

- New systems that can be added to these commercial technologies, such as flue gas desulfurization and low-NO_x burners.
- New coal-fired power technologies, such as AFBC, CFBC, PFBC, coal gasification, and (coal-fired) gas turbines and diesel engines; each is explained below.

Atmospheric Fluidized Bed Combustion (AFBC). In fluidized bed combustion systems, fuel, limestone, and inert material (ash, sand, etc.) are suspended by an outflow of air in the combustion chamber such that the mass behaves like a (bubbling) fluid. Air is distributed beneath the bed. Water in tubes in the bed is converted to steam that can be used in power generation or process uses. The enhanced mixing, turbulence, and heat transfer to imbedded tubes allow combustion to take place at relatively low temperatures (1500 to 1700 °F), minimizing ash slagging and fusion. The bed parameters are selected to minimize solids carryover and keep the slurry particles fine.

Table 19

Large-Scale Cogeneration Manufacturers

ADEA STAL (Sweden)
BBC Brown Boveri & Co. (Switzerland)
Centrax (England)
Cullen Detroit Diesel Allison (British Columbia)
Deltak Corporation
Fiat TTG (Italy)
Franco Tosi Ingegneria (Italy)
Ingersoll-Rand
John Brown Engineering (Scotland)
Kongsberg North America
Kraftwerk Union (West Germany)
Mendenhall Technical Services
Mitsui (Japan)
Ruston Gas Turbines (England)
Skinner Engine
Solar Turbines
Stewart & Stevenson
Terry Steam Turbines
Thermo Electron
Turbine Energy and Service
Turbo Systems
Turbonetics Energy
Utility Power Corp.
Valley GM Power
Western Engine Co.

Fluidized bed combustion systems offer three important advantages: (1) sulfur can be captured in the furnaces as calcium sulfate, (2) emissions of nitrogen oxides are lower than in conventional boilers because of lower operating temperatures, and (3) a wide range of low-grade fuels can be burned in FBC systems. These major problem areas have been encountered and are being resolved: coal feeding, and failure of in-bed tubes.

Circulating Fluidized Bed Combustion (CFBC). In a CFBC, bed parameters are selected to promote recirculation. Because these beds operate at high velocity, they are sometimes referred to as fast fluidized beds. Their principal advantages are longer residence times, which increase combustion efficiency and emission control; use of larger fuel particles, which saves in fuel preparation costs; and use of finer limestone particles (increasing their utilization because they no longer escape into the flue gas). This design also eliminates many problems associated with fuel feeding. The shortcomings include a higher fan power requirement, a need for additional protection of the in-bed tubes, and the potential blockage of the mixing mechanism by fuel particles. The stage of development of CFBC is essentially similar to that of AFBC.

Pressurized Fluidized Bed Combustion (PFBC). This technology is similar to AFBC, except it operates at high pressure (about 100 psi). This offers two advantages: (1) the

combustion products can be expanded through a turbine to produce power, thus increasing the efficiency, and (2) the boiler is sufficiently compact to be shop-fabricated in modules that can be transported by barge or railroad (although the overall pressure envelope is still likely to be erected in the field. A design variation is the turbocharged PFBC, which has two turbines. The combustion turbine output is used entirely for gas compression, while the steam turbine output is used for electricity generation.

Integrated Coal Gasification Combined Cycle (IGCC). This technology combines coal gasification with the proven, efficient gas turbine/steam turbine combined cycle. Gasification and flue gas cleanup systems can be thermally integrated with the steam cycle. Plants can also be designed without thermal integration. The basic function has been demonstrated in a 100 Mw plant. Fully optimized plants are in the planning phase at two utilities in the United States. The major advantages include fuel flexibility, high efficiency, and easier SO_2 control (prior to combustion). Also, this technology lends itself to phased construction.

Coal-Fired Gas Turbine. This technology is in the R&D stage. Fine (micron-sized) low-ash coal is injected (dry or slurried) directly into the gas turbine combustor. The hot combustion products are expanded through a turbine. A major concern is the life of the blades, given the corrosive, ash-laden gas streams. An important design variation is the indirect-fired gas turbine where an external heat exchanger is used to transfer heat between the products of combustion and the working fluid in the turbine. This protects the turbine blades.

Coal-Fired Diesel. This technology is also in the R&D stage. Fine (micron-sized) low-ash coal is injected (dry or slurried) into a diesel engine cylinder. The hot combustion products expand through the cylinder, producing power. The major problems are that the coal plugs the fuel nozzles and deposits ash on the cylinder walls. Ongoing R&D involves stationary and locomotive diesel applications.

Technology Status/Commercial Availability

The status of the development of the above technologies is summarized in Table 20. Over 100 units of AFBC/CFBC systems have been installed in industrial applications for steam raising and cogeneration over a broad size range. Two AFBC and one CFBC utility power plants, ranging from 110 to 160 MW, are under demonstration. The industry will be watching the results of these demonstration projects and evaluating data collected on numerous smaller industrial and cogeneration systems.

AFBC and CFBC are already available for commercial applications (from small packaged units to field erected units of up to one million lb of steam/hr).

Firms involved in the commercialization of FBC systems include the traditional suppliers to the boiler industry, other companies in the metallurgical and chemical industries, and many technology-based companies. Many innovative FBC designs have been developed in the United States and abroad. About 14 organizations and manufacturers offer FBC boilers in the United States. Many of these manufacturers offer imported technologies under license or in cooperation with overseas manufacturers. Major FBC boiler manufacturers include:

- Babcock & Wilcox
- Combustion Engineering

Table 20

Coal-Fired Power Systems

Technology	Status	Major U.S. Industry Participants	Who Is Funding	Comments
Atmospheric/circulation fluidized-bed combustion (AFBC/CFBC)	• Commercial for industrial units • Demonstration for utility-scale units	Pyropower Babcock & Wilcox Combustion Eng. Foster Wheeler Riley Stoker Dorr Oliver	DOE/METC EPRI	Leading emerging Power technology suitable for U.S. Army installations
PFBC	Demonstration	- Babcock & Wilcox - Combustion Eng. - American Electric Power Co.	DOE EPRI	Commercial after the turn of the century; suitable for large power plants
IGCC	Commercial	Texaco, Shell Dow, Potomac Power Co.	DOE EPRI	Suitable for large power plants
Coal-fire gas turbine	R & D stage	- General Electric - Westinghouse	DOE	Turbine blade protection is a major hurdle
Coal-fire diesel	R & D stage	General Electric Thermo Electron Cooper/A. D. Little	DOE/METC	Major hurdles that need to be overcome are: - plugging of coal nozzles - adverse impact of ash on cylinder

- Foster Wheeler
- Riley Stoker
- Keeler/Dorr Oliver Boiler
- Fluidyne Engineering
- Energy Products of Idaho
- Combustion Power
- Pyropower
- Power Recovery Systems.

As for the other, non-FBC technologies discussed above, a demonstration of PFBC technology at a U.S. utility (at 70 MW) is planned and results are expected by the late 1990's. The industry will be watching this demonstration very closely before placing any commercial orders. Two IGCC projects have been ordered in the United States. Gas-fired combined cycle units will be erected first and will produce power. Then the coal gasifier and the cleanup systems will be added to convert the plant to coal and increase its output to full capacity. Coal-fired gas turbines and diesel engines are still in the R&D stage. They are are not likely to be available commercially for quite some time.

Development Programs/Funding Organizations

The major funding organizations of coal-fired power technologies are DOE, EPRI, and the major coal-producing states (Ohio, Indiana, and Illinois). For example, the current DOE Clean Coal Technology Program has committed $360 million over 3 years for nine demonstration projects involving a variety of programs. Industry is sharing the cost of these projects at the level of $600 million. This funding is expected to continue and increase over the next 5 to 10 years. Also, EPRI has spent several hundred million dollars over the past several years.

Major Performance/Cost Issues

When compared to conventional technologies with pollution control equipment (such as pulverized coal/flue gas desulfurization), AFBC/CFBC systems offer slightly lower capital investments and permit more compact construction (because of their characteristically high heat transfer rates). AFBC/CFBC boilers (especially CFBC) can generally handle a broader range of fuels, including low-grade peats, lignites, and waste fuels. However, the economics of operating fluidized beds with high-sulfur fuels are sensitive to the calcium-sulfur ratios for effective sulfur emissions control. Such economics will be determined with certainty after enough data have been collected from the various ongoing projects.

Possible Army Applications

AFBC and CFBC lead the other technologies in their state of development and their potential application to U.S. Army facilities for steam raising and cogeneration. PFBC and IGCC are suitable for large utility-size power plants, so they are not likely to find applications in the Army. Coal-fired gas turbines and diesel engines place stringent requirements on fuel properties, but would be applicable to modular construction at installations.

Fuel Cells

Technology Description

A fuel cell is an energy conversion device that converts the chemical energy of a fuel and oxidant into electricity through continuous electrochemical process. Like a fuel-fired generator, a fuel cell generates power from a continuous feed of fuel and oxidant, and exhausts a continuous stream of oxidation products.

Extensive work has been done on cells for space craft, but three basic types are actively being developed for terrestrial applications. Identified by electrolyte, they are referred to as phosphoric acid cells, molten carbonate fuel cells (CFCs), and solid oxide fuel cells (SOFCs). Although their operating conditions are somewhat different, the basic principles of operation are quite similar. The fuel cells themselves produce direct current. For most uses, this power is inverted to produce the alternating current required by most standard household appliances (60 Hz in the United States). This is accomplished with a solid state inverter.

Fuel cells offer very high power generation energy efficiencies. They convert energy isothermally (i.e., at constant temperature). Therefore, their efficiency is not limited by the Carnot cycle. Theoretically, nearly all of the chemical energy in the fuel can be converted to electricity. The maximum theoretical efficiency of a fuel cell running on hydrogen is about 95 percent, compared to 40 to 50 percent for heat engines. However, for a practical fuel cell system designed to run on natural gas, the fuel-to-net-electricity efficiency is in the range of 38 to 40 percent, still an improvement over practical conventional systems.

Fuel cell conversion systems have several features which make them attractive candidates for dispersed power generation:

- Easy to site. Fuel cell power plants are environmentally clean compared to other generating systems. Gaseous emissions consist mainly of water vapor and carbon dioxide with negligible amounts of hydrocarbons, nitrogen oxides and sulfur oxides. They produce no liquid waste streams and are also relatively quiet.

- Easy to construct. Fuel cell power plants lend themselves to factory assembly. It is envisioned that preassembled modules will be delivered to the site for final installation. This will reduce lead time and construction costs for incremental generating capacity.

- Better load management. The efficiency versus load characteristic for a fuel cell is nearly constant between 20 and 100 percent of load. Therefore, a fuel cell can be modulated over a wide load range without loss of fuel efficiency.

- Unattended operation. Currently, fuel cell power plants are being designed to follow the load automatically, without onsite operator assistance. This is of particular significance for remote power generation applications.

- Reduced cost. The dynamic and siting benefits of fuel cells result in costs $100/kW less than combined cycles.

Technology Status/Commercial Availability

CFCs are further developed than solid oxide systems; however, major development efforts are needed in the cell stack area (power section) before CFCs can be commercialized. These include issues that have long development times and represent major technological hurdles: cathode solubility, electrolyte loss, corrosion, and thermal cycling. Molten CFC technology is being adequately supported for application in central station electricity generation by EPRI and other groups in universities, research facilities, and utilities. The SOFCs appear particularly promising to GRI because of (1) its ability to use methane directly without extensive reformer (processing) equipment, and (2) its potential for development as a simpler and possibly less expensive system.

Major development efforts are also required before the SOFC system can be commercialized. Currently, these R&D needs are fundamental and include cell fabrication, electrical interconnect, thermal cycling, internal electrical losses, scale-up, system component integration, direct methane use, and heat recovery. These issues must be resolved before detailed SOFC system development can be undertaken. However, the SOFC has the potential to provide energy services in small sizes appropriate to onsite cogeneration at industrial and commercial facilities.

GRI has already installed and monitored forty-six 40-kW phosphoric acid fuel cells. Units operated for an average of 5,500 hours per unit. Five units have exceeded the test goal of 8,000 hours. The average unadjusted online operation has been 63 percent. International Fuel Cells (IFC) will be assisting in the initial commercial offering of 200-kW phosphoric acid fuel cells. Based on the field tests it is expected that this size will be more economical. The use of fuel cells for remote, distributed power generation is technically feasible today; the major obstacle is economics.

Development Programs/Funding Organizations

DOE and EPRI are funding research with advanced fuel cells such as the CFC and SOFC that appear promising. These systems are fueled with gas derived from coal gasifiers. Most of DOE and EPRI's efforts are focused at resolving basic cell structure and stack operation issues such as chemical and physical stability, ancillary component development, and system integration development. EPRI is planning to cofund bench-scale development of a 100-kW internal reforming molten CFC. They expect to test it by 1990. GRI's efforts are aimed at advanced fuel cells that use methane for cogeneration applications. The 1987 budget for fuel cells was approximately $8 million at GRI, $6 million in government funds, $7 million in industry funds, and $4 million at EPRI. Major U.S. and Japanese companies involved in fuel cell R&D are shown in Table 21.

Major Cost/Performance Issues

Advanced fuel cells (such as CFCs and solid oxide fuel cells) operate at higher temperatures than phosphoric acid fuel cells (1300 to 2000 °F vs. 400 °F) and can provide higher-quality thermal energy. In addition, these advanced fuel cells can achieve electrical efficiencies in the range of 45 to 63 percent (high heating value [HHV]) compared with 38 to 40 percent for phosphoric acid fuel cells. Advanced fuel cells range in sizes from a few kilowatts to several megawatts. If used in appropriate residential, commercial, and industrial markets, they could yield substantial energy savings for end users and displace coal and oil with natural gas.

The most significant performance feature of the fuel cell power plant is its energy conversion efficiency. The intrinsic electrical efficiency of a fuel cell is typically in the

90 percent range. However, when current is drawn from the cell during operation, other sources of inefficiency come into effect*. With these effects minimized, cell stack efficiencies of 55 to 60 percent can be achieved. If the inefficiencies of the fuel processor and system integration are also taken into account, the electrical efficiency falls further to about 40 percent. However, quite often a portion of the wasted heat can be used for space heating. In such instances, the overall energy efficiency can approach 80 percent depending on thermal demand.

The major barrier to the widespread use of fuel cells is cost reduction. Currently, fuel cells are not cost effective for many applications. Improvements in the technology along with reduced capital costs could generate a large market potential for this technology.

Possible Army Applications

Fuel cells could be widely applied in Army facilities when the cost is reduced to acceptable levels. Examples include

- Cogeneration units in an individual building or clusters of buildings
- Central power units (possibly combined with district heating) using natural gas or, in the future, coal-derived fuel
- As primary power sources in industrial applications--particularly where direct current can be used directly (DC motors, electrolysis, etc.).

The low noise levels and potentially high efficiencies of fuel cells make them an exciting option for future applications once their system cost is reduced to under about $1500/kW.

High Efficiency Motors

Technology Description

Most electric motors are induction motors. Motors rated less than 1 hp typically operate from a single-phase supply, whereas integral hp motors operate from three-phase supplies. In either case, the stator consists of a stack of steel laminations in which slots have been punched before stacking. After stacking, a polyphase winding consisting of coils of insulated copper wires is inserted in the stator slots. The rotor consists of another stack of laminations having slots surrounding the periphery which are filled with aluminum and joined by aluminum rings at either end of the stack. The rotor assembly is attached to a shaft that in turn is supported on bearings in the stator housing.

These are sources of loss within an induction motor:

- Hysteresis and eddy current losses in the stator and rotor laminations
- Ohmic (I^2R) losses in the copper stator winding and rotor aluminum bars
- Windage
- Bearing friction.

***These inefficiencies are caused by activation and concentration polarizations and by internal electrical resistance losses.**

Table 21

Fuel Cell R&D Companies

Phosphoric Acid

- International Fuel Cells (South Windsor, CN)
- Westinghouse Research & Development (Pittsburgh, PA)
- Englehard (Edison, NJ)
- Energy Research Corporation (Danbury, CN)

Japan: Toshiba, Fuji, Sanyo, Hitachi, Mitsubishi, KEPCO, CEPCO

Molten Carbonate

- International Fuel Cells
- Energy Research Corporation
- Institute of Gas Technology (IGT) (Chicago, IL)

Japan: Hitachi, Toshiba, Mitsubishi, Fuji, IHI, CRIEPI

Solid Oxide

- International Fuel Cells
- IGT
- Garrett Air Research (Torrence, CA)
- Argonne National Labs
- Ceramatec (Salt Lake City, UT)
- ZTEK (Waltham Pond, MA)
- Major U.S. oil companies

Japan: National Laboratories (ETL, NCLI, GIRIO)

To improve the efficiency of a motor, these losses must be minimized, either by using better materials or by better design. For example, goals might be reduced current density in the windings or reduced flux density in the laminations. Unfortunately, either improvement method increases manufacturing costs.

Technology Status/Commercial Availability

Following the oil crisis in the early 1970's, most major motor manufacturers developed a line of high efficiency motors. They achieved this by redesigning their standard motors. The improvements in efficiency were in general approximately 5 to 7 percent in small horsepower motors, and less at larger ratings. Even so, depending on the application, the savings in electric power usage can justify the higher cost of a high efficiency motor.

Development Programs/Funding Organizations

Although most of the major motor manufacturers (Table 22) have developed their own induction motor design programs for optimizing efficiency, EPRI has funded a number of recent programs directed towards improved motor efficiency.

Table 22

High Efficiency Motor Manufacturers

General Electric Company
Westinghouse Electric Corporation
Reliance Electric
Century Electric, Inc.
Siemens - Allis
U.S. Electric Motors
Baldor

The results of one project were published in July 1985 *Optimization of Induction Motor Efficiency Volue I, Three-Phase Induction Motors.* A computer program that was developed is available through EPRI. One important finding from the study was that design optimization generally increased efficiency more than simply adding material, e.g., increasing the size of the motor frame size. Furthermore, the study demonstrated that a relatively large increase in production cost is necessary to modestly increase efficiency. In general, high efficiency motors have a premium price increase of about 25 percent over conventional units. Improved materials can also improve motor efficiency. The laminations used in the stator and rotor stacks are made from a silicon-iron material. Eddy current and hysteresis losses can be reduced somewhat by using thin laminations made from high-silicon steel. This will not produce dramatic losses. On the other hand, using an amorphous metal for the laminations could significantly reduce eddy current and hysteresis losses. Unfortunately, it is extremely difficult and costly to punch slots in amorphous metals. As a result no one has found a good way to use amorphous metals for making motor laminations. Even so, amorphous metals are being used in the electric industry for experimental transformers, where they appear promising. The amorphous metal used is called Metglass.* EPRI has been a principal sponsor of the transformer project. These materials may have applications in future motors. Improved conductors can reduce ohmic losses. Copper and aluminum will continue to be used as conductors, but the new high temperature (90 K) superconducing ceramic materials are receiving increased interest. There may eventually be room temperature superconductors, but these would have to be formed into wires or films to be useful in motors. It is doubtful they will ever be suitable for motors since most superconductors do not remain superconducting in the presence of an alternating field such as that in an induction motor.

Major Cost/Performance Issues

To determine the benefit of using high efficiency motors, one has to consider each application individually. For applications where the motor uses large amounts of power, a high efficiency motor may have a relatively fast payback. This assumes that electric energy is relatively expensive. Large hp motors are an exception since they normally have a relatively high efficiency anyway. In general, high efficiency small motors (10 hp

*Allied Corporation registered trademark.

or less) have a payback of a year if they are operated at rated load for a significant portion of the year. This is based on an energy cost of $0.05/kWh. If the energy cost is higher or the usage is higher, payback occurs sooner.

Possible Army Applications

It should be recognized that retrofitting existing Army motor applications with high efficiency motors is probably not economically justified, since the entire cost of the high efficiency motor and not just the incremental cost would be of concern in calculating the payback period. This assumes that the existing motor would have little value. Applications are primarily for motors that run continuously. Economic benefits must be considered for each situation.

5 INDUSTRIAL SYSTEMS

High Temperature Recuperators

Technology Description

Heat exchangers are the basis for waste heat recovery in high efficiency systems. Conventional heat exchangers, though, cannot be used in very high temperature applications (over 1000 °F) without some sort of precooling. But radiating the outgoing air to the environment wastes useful heat, and decreases efficiency. A high temperature recuperator can be used to process the hot air directly. These devices are constructed of a variety of materials according to temperature applications, and can be grouped under the following major classifications:

- High temperature ceramic recuperators
- Advanced metallic recuperators
- Special applications.

For heat recovery at temperatures 1700 °F and above, metallic recuperators cannot be used because of their temperature limitations. Ceramic materials are used instead. One recuperator concept under development consists of a vertical, cylindrical heat exchange column formed from modular sections. Within the column, the modules form two helical flow passages--one for high temperature exhaust gases and one for preheating combustion air. The column is operated in a counterflow mode, with the exhaust gas entering at the bottom and combustion air entering at the top. Figure 4 shows a schematic drawing of the modular counterflow recuperator with a helical interface. Many ceramic modules or tubular sections are stacked together to form the recuperator. The number of modules and the length of each module are functions of the exhaust flow rate temperature and heat transfer effectiveness for a given application.

Advanced metallic recuperators bridge the gap in operating temperature between conventional metallic and ceramic recuperators. The recuperators use high-chromium stainless steels. They are capable of operating at temperatures up to 1700 °F with 1400 °F combustion air preheat. The recuperators achieve high heat transfer effectiveness by optimizing the mean temperature difference between the flow streams.

A problem with ceramic recuperators is that supporting burner technology is not developed. High temperature burners for using high temperature combustion air have not been developed. It is meaningless to preheat the air to such a high temperature if it cannot be used once it is there.

Most high temperature applications have dust-laden flue gas that plugs and corrodes ceramic recuperators. Better cleaning techniques are required to keep recuperators operating in dust-laden gas applications. The variety of special applications of recuperator techniques is too diverse to summarize here. However, many unique designs are showing high efficiencies and low payback times in their research stages.

Technology Status/Commercial Availability

High temperature ceramic recuperators are now commercially available and are being installed by some firms. However, problems exist with leakage, cracking, and

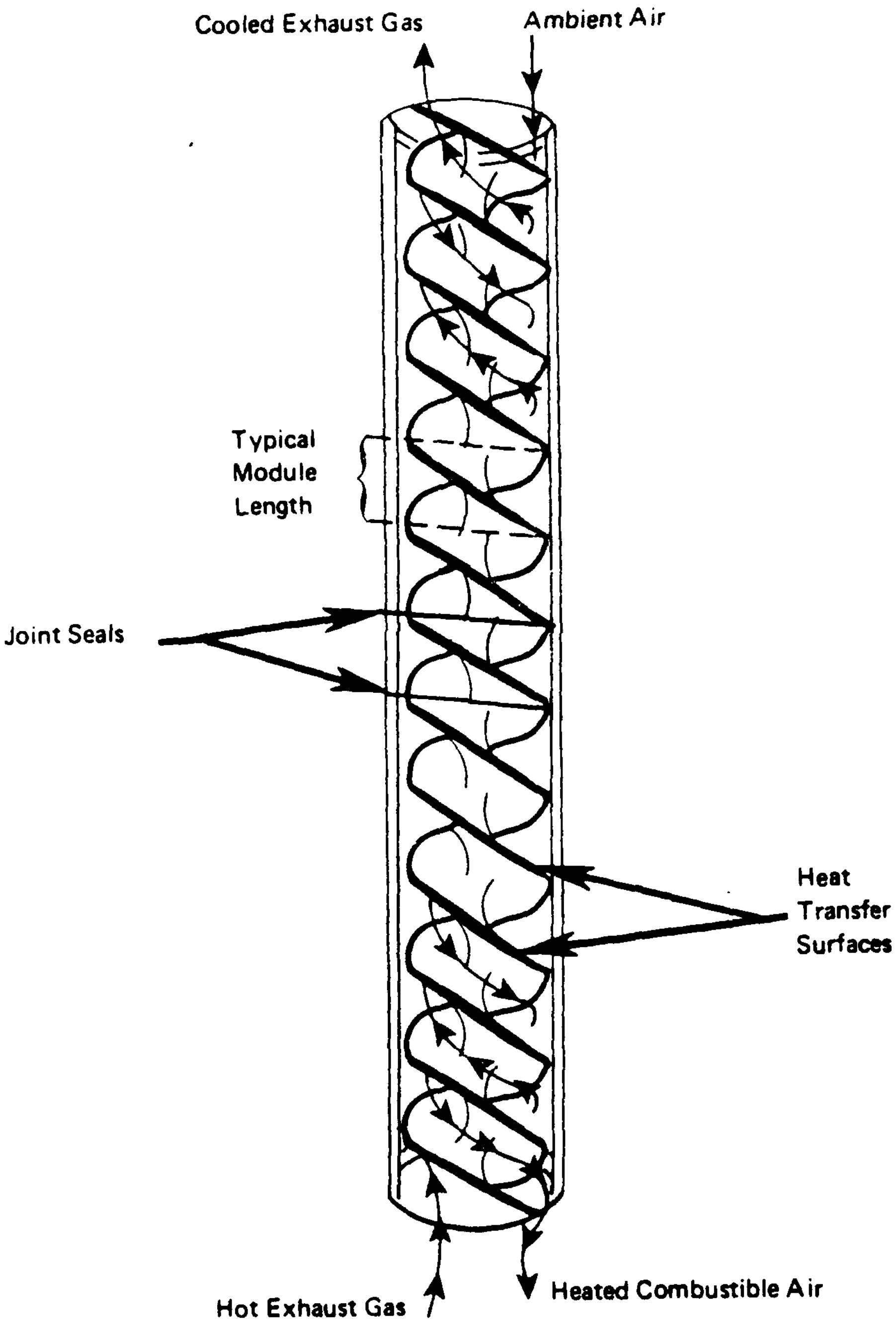


Figure 4. Schematic of the modular counterflow recuperator with a helical interface

fouling. Cleaning these recuperators can be difficult due to their brittleness. Start-up problems have been reported. Payback periods are acceptable, and there is tremendous potential for energy savings.

In many applications, advanced metallic recuperators could be more energy efficient than ceramic recuperators, even if the metallic recuperators cannot recover energy from very high temperature exhaust gas unless the gas is cooled. Most technical problems with advanced metallic recuperators have been solved. Efficiency improvements are nearly as high as the condensing devices, and the technology is applicable to much higher temperatures than condensing units. The operating temperature of metallic recuperators is dramatically increasing. The more durable and refined metallic exchangers are being used in what have been considered ceramic applications.

The ceramic recuperator in particular will need more development to achieve reliable and inexpensive operation over the long term. As newer composite materials are used in constructing ceramic materials, durability will be less of a problem, and ceramic recuperators will become a more viable regenerating alternative.

Development Programs/Funding Organizations

Because of their enormous potential for energy savings, high temperature recuperators have become the object of much research and development. GRI, DOE, and NYSERDA are funding large government R&D programs. General Telephone and Electric (GTE), Terra Tek, Inc. and Solar Turbines, Inc. are financing large corporate research efforts.

Major Cost/Performance Issues

Ceramic recuperators are being marketed by GTE, Midland Ross, Hague International, and C&H Combustion. GTE's ceramic recuperator can withstand flue gas temperatures from 1400 to 2400 °F and can be used on furnaces ranging from 0.5 to 2 MMBtu/hr. The installed cost of this recuperator is roughly $40,000/MMBtu/hr. Hague International's ceramic shell and tube heat recovery system can safely withstand flue gas temperatures up to 2800 °F. These units range from 3 to 35 MMBtu/hr and their installed costs range between $35,000 to $50,000/MMBtu/hr. C&H Combustion markets recuperators only as a package to be installed on a new furnace. The shell and tube system can withstand flue temperatures up to 2400 °F and can be used on furnaces ranging from 0.2 to 50 MMBtu/hr.

One problem with these systems is that their first cost is a very large fraction of the cost of the furnace on which they are to be mounted. Typically, a new burner, new fan, new controls, and new duct-work must be installed with the recuperator. This is apparently quite discouraging to potential commercial operators, even though the payback period is acceptable. Due to the extensive rebuilding of the furnace that is required, the feasibility of retrofitting has been rated low.

Possible Army Applications

Munitions facilities that produce propellants, explosives, and metal parts use high temperature processes that would benefit from more advanced high efficiency, high temperature recuperators. Preparing propellants and explosives, in particular, requires hot gas processes such as incineration and inert gas separation, and direct heat operations such as drying and curing. Making metal parts requires forging, where heat is available to be recovered. Many of these applications already use old high temperature recuperators that would benefit from replacement with new and more efficient units.

Condensing Heat Exchangers

Technology Description

One way of improving the efficiency of heating is recovering the latent heat of vaporization from the gaseous products of combustion, The exhaust gas temperature is lowered by passing it through a heat exchanger, where it warms the return water or combustion air for the boiler. This exchange saves sensible heat as the temperature decreases, and when the flue gas reaches its dewpoint, it condenses, releasing its latent heat of vaporization as well. Because flue gas condensate is very acidic, the heat exchanger must be made of corrosion resistant materials.

Technology Status/Commercial Availability

The main difference between a conventional heat exchanger and a condensing one is the latter's ability to withstand the corrosive properties of condensed acids. These exchangers are made of corrosion resistant material or specially coated. Materials presently used are aluminum, stainless steel, cast iron, and ceramics. Stainless steel and aluminum are both fairly resistant to acidic corrosion but will pit and break down eventually. Cast iron has no outstanding resistance to corrosion, but the considerable thickness of the material insures an acceptable operating life. Ceramics are being used with varying amounts of success. They are very resistant to corrosion and can withstand extremely high temperatures. However, durability and ease of servicing are major concerns. Coatings for conventional heat exchangers include Teflon, Rippolin, or a variety of polymers. Teflon is expensive, and the resistance of polymers to corrosion is still unknown.

CHX is the only company in the United States with considerable experience with condensing heat exchangers. It is likely that newer polymer coatings will be developed in the next 3 to 5 years that will withstand higher temperatures and worse corrosion. In that time, heat exchangers with improved corrosion resistant coatings may be commercialized. Until that time, conventional materials with a very definite life span will be available for short term/short payback applications.

Development Programs/Funding Organizations

Many organizations and corporations are funding R&D programs involving condensing technology, including GRI, NYSERDA and Brookhaven National Laboratory. With the exception of CHX in the United States, most corporate research is based in Europe. Froling Reatherm and Zantingh in Germany, Secaucier in France, and Fagersta all produce working heat exchangers and fund inhouse R&D.

Major Cost/Performance Issues

Heat exchangers are becoming important as their efficiencies approach 90 percent, because retrieving the maximum amount of energy from the flue gas is essential. A condensing heat exchanger can cut energy costs and increase efficiency when used in the right application. However, a conventional heat exchanger will also work reasonably well, while offering more durability and requiring less maintenance. Installed costs of condensing heat exchangers can range from $40,000 to $60,000/MBtu/hr recovered. Typical payback periods range from 1.5 to 3.5 years, depending on operating time. Considerably higher costs may accrue if flue gas must be cleaned before entering the exchanger. Overcoming pressure drops and periodic cleaning are significant recurring maintenance costs, which typically range from $800 to $1,500/MMBtu year. What must

be decided is if those last few percentage points of efficiency will pay for themselves in a reasonable period of time.

Possible Army Applications

USACERL's ongoing Facilities Engineering Applications Program (FEAP) project on "Heat Recovery at Industrial Facilities" (Mr. T. Pierce, Principal Investigator) has already helped identify many applications for condensing heat exchangers in Army industrial production facilities. In such cases, the condensing heat exchangers are used to improve the efficiency of large boilers by using low temperature exhaust heat to heat makeup water.

Condensing heat exchangers should also be considered for use in all facilities that have large hot water loads and that have central boilers (living quarters, health facilities, and dining halls). In such facilities, the additional energy recovered from boiler flue gas could be used to preheat domestic hot water supplies which are a year-long load (compared to space heating, which is highly seasonal).

Industrial Heat Pumps

Technology Description

Of the trillions of Btus of energy consumed by industry every day, less than one-third of the heat produced becomes useful work. The rest is dispersed into the atmosphere as hot air, or rejected to the environment as warm (90 to 200 °F) waste water. New technologies can be brought into play to recover some of this waste heat. In the case of warm water (cooling or condensate), a heat pump can be introduced to the system to recycle low quality heat into a more usable form. For industrial purposes, there are four basic heat pump formats:

1. Closed cycle vapor compression
2. Open cycle vapor compression
3. Mechanical vapor compression
4. Absorption.

The variety of heat pump options is further complicated by an array of different prime movers available. The system can be driven by electricity, natural gas, gasoline, or diesel. Every industry application is unique, and a heat pump system must be tailored to the output needs, input quality, and relative fuel prices.

Technology Status/Commercial Availability

To date approximately 500 industrial heat pumps of the first three types have been installed. Typical applications have included:

- Providing process and space heat in wastewater treatment plants, using sewage and sludge as the heat source.
- Generating 35 psig process steam in a chemical plant's plastics operation, using hot condensate as the heat source.

- Providing process hot water from cooling tower water in various food processing plants.

In addition to the above systems, heat pumps using steam ejectors and chemical storage are also either in limited use or under development. Presently, vapor compression and recompression heat pumps are the only configurations generally available for industrial waste heat recovery applications.

Table 23 lists the present suppliers of industrial heat pumps. This list should be used with caution since new manufacturers are expected to enter the market as the application of industrial heat pumps becomes more widespread. Also, several developments in advanced, higher-temperature vapor compression units, absorption systems, and chemical heat pumps may reach the commercialization stage over the next few years. Presently, approximately 200 closed-cycle industrial heat pumps are in operation. The number of site-erected mechanical vapor recompression units is hard to estimate but is probably a few hundred. Thus, major U.S. manufacturers already have considerable experience with both closed- and open-cycle industrial heat pumps. This provides potential users with an increasingly wide choice of system options and suppliers.

Development Programs/Funding Organizations

Heat pumps are becoming very important as the next major step in increasing efficiency in industry applications. Many organizations have substantially increased the funding and research in this area. DOE and NYSERDA have been conducting a significant amount of heat pump research, while GRI has become very involved in the development of efficient gas-fired systems. Many corporations (Table 23) are also involved in heat pump research and development.

Major Cost/Performance Issues

As noted in Table 23, several major firms offer closed-cycle industrial heat pumps. These systems generally have the capability of producing 220 °F hot water from waste heat sources at 90 to 120 °F. Firms producing closed-cycle equipment include McQuay-Perfex, York, and Carrier. Prepackaged, open-cycle industrial heat pumps are offered by General Electric and Thermo Electron Corporations. These units can deliver steam up to 450 °F when using a heat source with vapor temperatures of 212 °F or lower. Heat pumps are a significant capital investment, and unless a study of the particular application is done, it is hard to know which system is most economically feasible. Industrial heat pumps can be an attractive investment in properly selected applications, and if energy costs resume their upward trend, the economics of industrial heat pumps will improve further. The major issues being addressed to improve industrial heat pumps are piping, load balancing, and cost reduction. The remaining economic barriers for industrial heat pump systems are the high installation costs, due to site specific applications, and the sometimes poor gas-to-fossil-fuel price ratio.

Possible Army Applications

Industrial heat pumps have potential application in propellant and explosive manufacturing. Open-cycle heat pumps can be used for evaporators and distillation systems. Closed-cycle heat pumps can be used for drying propellant and explosives. The working fluids of open-cycle heat pumps may be a problem because they are so corrosive. It may be necessary to use specialty materials, which in turn would increase costs. A special design might also increase the cost of the heat pump system.

Table 23

Suppliers of Prepackaged Industrial Heat Pumps

		Temperature/Capacity Ranges					
Organization/Product	Generic Type	Source Temp-°F	Delivery Temp-°F (1)	Capacity 10^6 Btu/hr	Temp. Levels-°F Source/Del'y.	COP	Capacity 10^6 Btu/hr
McQuay Templifier	Closed Cycle	45-130	120-220	1-10	130/220	3.4 (2)	10
Carrier Heat Machine	Closed Cycle	40-140	90-160	1-2.8	85/140	3.6 (2)	2.5
Techmark Cyclotherm	High Temperature Closed Cycle	160 (min)	353 (max)	3.7-74	284/353	4.5 (2)	10
York — High Level	Closed Cycle	85-100	170-250	up to 74	140/200	4.4 (2)	74
Heat Pumps	Open Cycle	180-220	280-320				
Thermo Electron Industrial Gas-Fired Heat Pump System	Open Cycle (Gas Engine Driven Screw Compressor)	~190 (min)	~450 (max)	4-45	250 (30 psi)/ 330 (100 psi)	5 (2)	45
General Electric Open Cycle Steam Heat Pump	Open Cycle	140-150 (min)	~360	10-60	195 (7 psi)/ 310 (74 psi)	4.2 (2)	28
H.P.D., Inc. Custom Design Equipment	Open Cycle	160-280	~300	5-150	270/300	~9 (2)	—
	Steam Ejectors	250-280	~300		270/300	~1.9 (3)	

Notes:

1. Temperatures given represent leaving temperatures for closed cycles; steam saturation temperatures for open cycle.
2. Mechanical COP defined as heat output/work input.
3. Thermal COP defined as heat output/heat input.

6 RENEWABLE ENERGY

Photovoltaics

Technology Description

A photovoltaic (PV) system produces direct current (DC) electric power directly from sunlight using semiconductor materials. These systems do not have any moving parts or complex machinery, unlike solar power systems based on thermal processes (e.g., ones using concentrated solar energy or Rankine cycle power plants). The electric power generated is directly proportional to the amount of solar insolation intercepted by the PV system and is, therefore, directly proportional to the area of solar cell material and the solar insolation available. Since PV systems contain no moving parts, they are particularly suitable for use in remote areas, where the major alternatives are using engine-driven generators or extending the grid, both of which are often costly.

Solar cells are constructed by processing thin sheets of semiconductor materials so that they produce free electrons when illuminated by solar energy. The semiconductor wafers have electrical grid structures attached to them to capture these electrons and make them into an electrical current in an external electrical circuit. Wafers produce electricity at 0.4 to 0.6 volts, depending on the material and its processing. The efficiency with which solar energy can be converted to electricity by the photovoltaic process depends on the atomic structure of the material. Typically it ranges from 10 to 20 percent for most semiconductor materials of practical interest.

A photovoltaic power system usually consists of a photovoltaic array, electronic controls, and energy storage. A schematic of a typical photovoltaic power system is shown in Figure 5. The primary energy conversion unit is the photovoltaic array which produces DC electricity. This DC energy can be applied directly to a load (i.e., DC motor, water pump, lights, etc.), converted to alternating current (AC) for use with conventional AC equipment, or stored for later use.

Technology Status/Commercial Availability

There are several thousand small PV systems installed worldwide to serve such applications as corrosion protection of pipelines and operation of remote communication equipment. There are at least 40 establishments worldwide either doing R&D, or manufacturing PV cell arrays and other components required for these systems. Complete packages are available from over a dozen manufacturers.

Single-crystal silicon, which is also commonly used throughout the computer and electronics industry, has been the preferred photovoltaic material for more than a decade. Its theory, technology, and application are well developed, and module efficiencies of 13 percent are routinely realized in commercially available panels.

The other material in widespread use is amorphous silicon. This thin film material has potentially lower cost than crystalline silicon, but still has lower demonstrated efficiency levels (8 to 9 percent) and material stability problems. It is, however, now widely used in consumer products such as calculators and watches where efficiency is not very important.

Alternative solar cell materials which are far along in their development are gallium arsenide, cadmium sulfide, and cadmium telluride. The primary incentive for

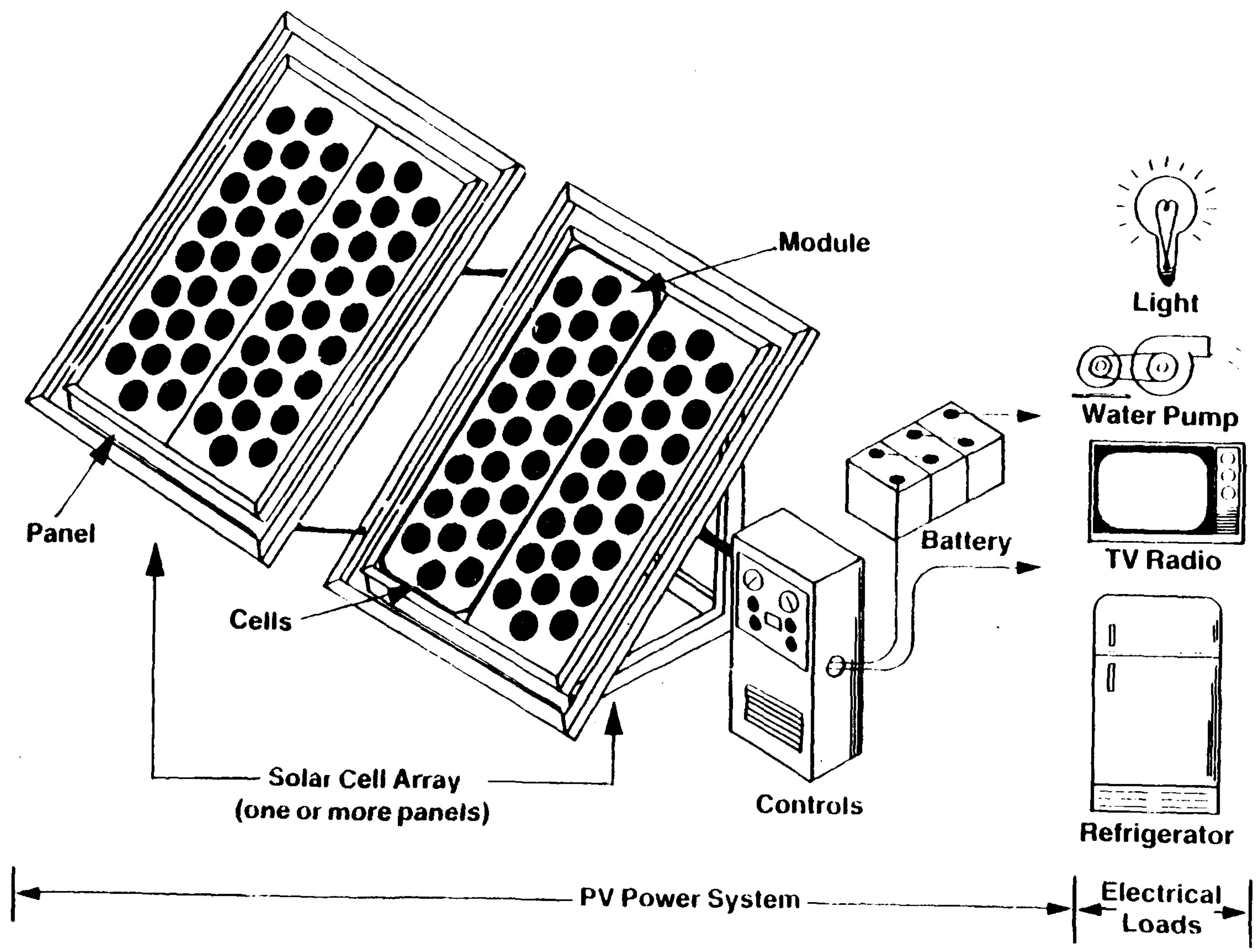


Figure 5. Schematic of photovoltaic power system.

developing these alternatives is that they can be used effectively in very thin films (2 to 10 microns), which is consistent with low cost manufacturing.

The current worldwide market for PV systems is about 29 MW per year. About 65 percent of this market is for remote power, 27 percent for consumer products, and 8 percent for government projects.

Development Programs/Funding Organizations

There are over 40 firms worldwide either manufacturing PV panels or undertaking PV material R&D. The industry is, however, dominated by a relatively small number of companies with the top four producers accounting for over 60 percent of production:

- Arco Solar (U.S.)
- Sanyo (Japan)
- Fuji (Japan)
- Solarex (United States).

A significant amount of R&D is being funded by the SERI through DOE. This research focuses on cell efficiency improvement and new materials. The EPRI also allocated $4.5 million in 1987 (increasing to $5.0 million in 1989) to demonstrate an economical utility grade PV power plant (10 to 100 MW) by 1995. In addition, their goals are to achieve PV costs of 6 to 8¢/kWh (constant 1986 dollars) by 1995.

Major Cost/Performance Issues

The major cost element of a PV array today is the photovoltaic panels. The mounting structure, panel wiring, installation, and miscellaneous parts currently represent less than 20 percent of the array cost. The cost of the panels will decrease as cheaper cell technologies and panel fabrication techniques are developed and as production increases. When this happens, the cost of the remaining components of a photovoltaic array will become relatively more important.

Presently, the cost of PV panels purchased in quantity (tens of kW of peak capacity) is approximately $6,000 to $10,000/peak kilowatt. For single panel purchases, costs are approximately $10,000 to $15,000/peak kilowatt. A reasonable projection for late 1980's panel costs is $2,000 to $5,000/peak kilowatt. Each peak kilowatt of installed PV system capacity results in 1200 to 1800 kWh of annual power production, depending on location and application details. If it is assumed that capital costs are amortized over 20 years and that O&M costs are very low (1 percent), the electricity cost for a PV system operating in a favorable area is about $1.10/kWh, based on current system costs of about $12,000/peak kilowatt. Solarex Corporation has already achieved conversion efficiency of 11.5 percent with single junction amorphous silicon and over 20 percent efficiency with various single crystal silicon technologies. Sanyo Electric in Japan also recently claims to have developed a see-through amorphous silicon solar cell which could result in entirely new PV products, such as window glass with power generating functions. Although these recent advances are not yet commercially available, it is expected that by the early 1990s PV costs will decrease significantly due to these efficiency improvements. With better efficiencies and technological improvements, the applications for PVs will grow significantly in the near to intermediate term.

Possible Army Applications

The power costs discussed above are generally still well above utility costs. In industrialized countries this limits the use of PV to special applications where utility power is not available. However, even with the current figures, PV may often be cost effective in Army applications for water pumping, aviation aids, battery charging, cathodic protection, firing range activities, telecommunications, and lighting.

As installed costs for PV systems decrease, PV will be able to serve more applications cost effectively. Grid applications for PV systems are likely to be cost effective in the near term as efficiency and degradation problems are resolved or improved.

Solar Hot Water Heating

Technology Description

The function of a solar water heater is to absorb solar radiation and convert it into useful heat for heating hot water. The main elements of a solar water heater are:

- A solar collector which absorbs solar radiation when available
- A means of storage (i.e., insulated water tank)
- An auxiliary energy source which accommodates demand beyond what the solar system can supply
- The necessary piping, controls, valves, pumps, etc., required to integrate the above elements into an operating system.

Solar collectors are configured to trap solar energy by maximizing the amount of incoming solar radiation absorbed, and by minimizing the energy dissipated as heat loss.

Technology Status/Commercial Availability

The technical feasibility of solar hot water collectors is well established. The three major types are thermosyphon, integral collection-storage, and forced circulation. In the thermosyphon and forced circulation types the storage, which is invariably potable water, is located away from the collectors and connected to them by either a direct or indirect heat-transfer loop. The reservoir of the integral collection storage system is always in direct thermal contact with the absorber. This storage may be either the potable water passing through the collector or a liquid separated from the potable water with a heat exchanger. Thermosyphon systems have the advantage of being self controlled: the natural circulation loop is driven by the solar heat, eliminating the need for a pump, controls, and auxiliary power. Although the thermosyphon system has the potential for low cost and high performance, it also requires that the storage tank be physically located above the collector, which frequently poses aesthetic and structural problems, and creates possible vulnerability to freezing. However, indirect thermosyphon systems using a phase change heat-transfer fluid can operate in freezing climates.

Solar hot water systems have been commercially available for many years in the United States. Table 24 lists some of the key solar collector manufacturers.

Development Programs/Funding Organizations

Solar hot water heating technology is well developed. As a result, many United States organizations have significantly reduced their research programs in this area. DOE and EPRI have some ongoing field monitoring programs, but overall funding in these organizations has switched to more embryonic technologies. The middle-Atlantic, southern, and western United States are just a few areas that have seen a wide use of solar hot water systems because they receive high levels of solar energy. It is not expected that funding for this activity will increase because the technology is already quite developed.

Major Cost/Performance Issues

Installed costs of solar water heaters vary widely with installer and manufacturer. There are some systematic variations that can be identified. Economy of scale plays a role. Cost per unit area tends to decrease with area, since certain cost components such as controls, piping, and some installation tasks are primarily fixed costs that depend very little on size. Systems designed for cold regions tend to cost more because they must be protected against freezing.

Solar water heaters achieve best performance when facing due south and tilted with respect to horizontal at an angle equal to the location's latitude. Precision is not critical: departures of 10 to 15 degrees in either azimuth or tilt will reduce annual solar eneregy collected by only a few percent. It is important that the collector not be shaded by trees or other structures at any time of the year.

Table 24

Solar Collector Manufacturers

- U.S. Solar Corporation
- Fafco
- Heliodyne
- Ramada Energy System
- Solarhart (Australia)
- Sun Resource Energy Systems
- Radco
- Mor-flo
- Solar Development
- American Energy Technologies (was Morningstar)

The installation of solar water heaters requires care in attaching collectors to the roof and in making the plumbing connections to avoid leaks in the roof or solar piping. Also, air vents and temperature sensors must be located properly, and the piping for drainback and draindown systems must be sloped carefully. Typical installed cost and performance for systems are shown in Figures 6 and 7.

Constraints on the widespread use of these systems include

- High installation costs
- Marginal economics
- Availability of adequate unshaded southern exposure where collectors can be conveniently attached
- Availability of adequate solar radiation (this degrades economic performance unless counterbalanced by high conventional fuel costs).

Possible Army Applications

The Army, in part through programs supported by USACERL, has demonstrated the technical performance of solar water heating on living quarters and common facilities buildings (USACERL TR E-194/ADA142678, *Domestic Hot Water System for Department of Defense Barracks*, March 84). High installation costs and declining energy prices have tended to result in marginal to poor economics of applications to date.

Nevertheless, incremental improvements in technology and cheaper installation procedures combined with rising energy costs in the future could make solar water heating economically attractive in the late 1980's or early 1990's. This could be especially true for applications with significant hot water demands, such as living quarters and dining facilities. The potential range of applications and associated energy use impacts is large, which should make this option one of continuing interest to the Army.

Wind Power Systems

Technology Description

Wind turbine (WT) electrical generators convert the kinetic energy of the wind into mechanical energy that drives a generator. Two common designs are standalone WTs combined with batteries to ensure power, and WTs that are connected to the utility grid. The latter has been more economical in the United States Many U.S. companies have developed "wind farms." This technology could easily be transferable to Army facilities.

Technology Status/Commercial Availability

Although there are several types of WT generators which have been used or are in the development stage, only two types of WT rotors are commercially available and application to Army facilities. These are the horizontal-axis wind turbines (HAWT) and the vertical-axis wind turbine (VAWT). Each type can be used to generate electricity or heat or to pump water.

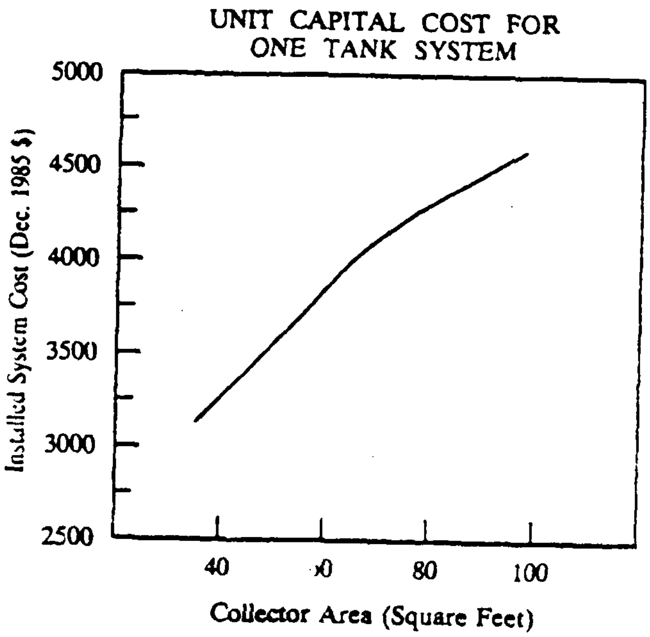


Figure 6. Cost of solar water heaters.

REGIONAL VARIATION FOR ONE TANK SYSEM

Location	Capital Cost (Dec. 1985 $)	Solar Fraction	Backup Energy (kWh/year)
Boston	3800	60%	2862
Atlanta	3800	78%	1327
Columbus	3800	70%	2020
Chicago	3800	56%	3005
Dallas/Ft. Worth	3250	81%	1057
Albuquerque	3250	84%	1024
Portland	3800	61%	2604

Figure 7. **Performance characteristics of solar water heaters.** Source: "TAG™ Technical Assessment Guide, Vol 2: Electricity End Use," EPRI P-4463-SR. Vol 2, Part 1 (Electric Power Research Institute, September 1987).

During the past few years, the WT technology has improved significantly due to the large wind farm activity in California. With the loss of the United States Federal tax credits for wind energy systems, manufacturers and developers have had to reduce O&M costs and correct mistakes that were made with the WT technology in the early 1980s. Today the technology is well understood and widely implemented.

Wind turbines have been commercially available for many years and widely used in California wind farms since 1980. Approximately 2,100 WTs were installed in California in 1986 alone, totalling 223 MW in capacity. In 1985 511 MW were installed. The three largest manufacturers represent 50 percent of all capacity: U.S. Windpower, Fayette, and Vestas. Table 25 lists the top 10 manufacturers and developers of WT systems.

Development Programs/Funding Organizations

In the early 1980's, DOE and EPRI funded a significant amount of R&D on large-scale WTs. More recently, however, DOE has focused its wind power budget on basic sciences such as aerodynamics, structural dynamics, and atmospheric fluid dynamics. The 1987 DOE wind energy budget was $16.7 million for these basic science programs and $10.9 for laboratory research at SERI, Sandia National Laboratory, and the Pacific Northwest Laboratory. EPRI had a 1987 budget of $0.6 million, a 1988 budget of $0.5 million and a 1989 budget plan of $0.6 million for wind research. Their primary role is to evaluate, document, and disseminate the field experience of state-of-the-art WT technology and to facilitate programs that involve utility-grade WTs and wind power stations, primarily in the small to intermediate size range.

Major Cost/Performance Issues

The major barrier to the widespread use of WTs is that few areas have both adequate wind regimes and available land. At Army installations, the wind speeds must be approximately 12 mph in order for WTs to be cost-effective. The available power in the wind is proportional to the cube of the wind velocity. However, only a fraction of the energy in the area swept by the blades of a WT is extracted as mechanical energy. A typical annual energy output for a 100-kW WT in California, in areas with wind regimes greater than 14 mph, is approximately 210,240 kWhs. The capacity factor for WTs averages between 15 to 25 percent due to the variations in wind velocities. With installed costs of WTs at approximately $1,000 to $1,500/kW the cost of energy (COE) is around 8 to 12 ¢/kWh.

Discussions with WT manufacturers and utility operators have indicated steadily increasing WT reliability. The technology has improved significantly over the past few years due to increased operational experience. Major improvements with the performance of the systems are not expected in the near term because the technology is currently well developed.

Possible Army Applications

Unlike solar energy, wind resources vary greatly over relatively short distances and, on average, are not sufficient to result in economical operation. However, for Army facilities located in fairly windy areas (average wind speeds greater than 12 mph), wind generators could economically provide supplemental power, with associated electric energy savings. Such installations might include those of selected coastal locations, in the plains areas of the United States or those in mountainous regions with locally high wind regimes. Assessing the potential for wind power at Army facilities would, however, require site-specific wind surveys to determine which, if any, are located in areas with sufficiently consistent wind regimes.

Table 25

Top Ten WT Manufacturers and Developers (1985)

Manufacturers	**Capacity (MWs)**
U.S. Windpower	180
Fayette	150
Vestas	140
FloWind	95
ESI	60
Micon	40
Bonus	30
Century	25
Carter	18
Windtech	17
Developers	
U.S. Windpower	180
Fayette	150
Zond	145
FloWind	95
Sandberg	45
Seawest	30
Cannon	28
Triad	25
Arbutus	22
Renewable Energy Ventures	22

Source: *Alternate Sources of Energy*, January 1987.

Passive Solar Building Design

Technology Description

Passive solar heating is a set of building practices and techniques for arranging architectural components which work together to gather and store energy from the sun. Many of the concepts of passive solar heating are not new and have been applied for many years, but some, such as phase change storage, involve newer materials or design ideas.

Passive solar heating can potentially cut fuel bills in buildings by 20 to 80 percent. The techniques are primarily applicable to new construction, since retrofitting is usually extensive. The reduction in fuel use is given as a broad range because it depends so heavily on individual designs.

Technology Status/Commercial Availability

Most passive heating techniques are not easily retrofitted to existing buildings. As the building stock is replaced during the next few decades, many passive design features will probably become standard. Heavy insulation and reduced north-facing windows, for example, are already widely followed building practices. Other common practices include increasing the internal thermal mass of a structure (i.e., using water walls, masonry floors etc.), attaching a sunspace, properly siting the building to orient it facing south/southwest, and incorporating skylights and clerestories.

A key measure of passive solar performance is the quantity of total heat load which can be obtained from solar energy. Each passive solar heated facility is unique. Facilities have been built using techniques ranging from simple south-facing windows to complex thermosiphon systems. The actual performance of a passive solar facility however, is not only a function of the specific design but also of local climate.

Passive solar heating techniques are technically feasible and widely applied throughout the United States. Hundreds of family housing units have been built that aim to provide 20 to 80 percent of their energy requirements from the sun, and certainly thousands have been built that avoid north-facing windows to minimize heat loss and use south-facing windows to maximize heat gain.

Development Programs/Funding Organizations

SERI, through DOE, undertook a significant amount of R&D for passive solar systems a few years ago. In recent years, however, the major funding at SERI has focused on photovoltaic R&D rather than passive solar technologies. Currently, most of the passive solar R&D activity that is being done is through private industry. Research on new materials is being pursued for advances in insulation and heat storage materials.

Major Cost/Performance Issues

The cost of passive solar heating is very site-specific, depending on local climate (solar radiation and temperature), building design and orientation, and the cost of construction. To assess the solar gain for any particular concept involves simulating of climatic conditions (hourly or daily) using calculation aids and/or a computer. The result is limited to the particular building analyzed and is difficult to extrapolate to another building, even in the same geographic area. As a result, there are very few examples in the literature which quantify the economics of passive solar systems. As a general rule of thumb, however, an additional cost of 10 to 15 percent of the total house cost is often assumed.

Possible Army Applications

The use of many passive solar techniques could and should be applied to new construction of Army buildings. Increasing south-facing window area, applying movable insulation to block the loss of energy through glazing at night, and increasing the internal thermal mass for heat storage are just a few examples of passive solar measures that would reduce heat loads and improve energy conservation in new Army buildings.

7 MISCELLANEOUS TECHNOLOGIES

Insulation Materials

Technology Description

New phenolic foam insulations are becoming a cost-effective alternative to the standard fiberglass batt insulation, especially in new construction. Phenolic foam is a rigid, board-like insulation best suited for new construction. It is lightweight, easy to handle, and has very good flame-spread and smoke qualities. The actual insulating value varies with the manufacturing methods and materials. Overall, there have not been significant advances in new insulation materials other than phenolic foams.

Technology Status/Commercial Availability

Phenolic foam is the fastest developing market among insulation options. This has brought a lot of new manufacturers and manufacturing techniques into the marketplace. Koppers Company was the first to sell closed-cell phenolic board insulation. It has a patented process that traps the freon blowing agent within the cells, further reducing heat transfer. Thermo-safe in San Antonio, TX also markets isocyanurate and closed cell-board insulation.

Development Programs/Funding Organizations

Insulation is a mature industry, and improvements come with the evolution of materials and application techniques. As such, most of the R&D is corporate. When manufacturers improve their product lines, independent laboratories are usually involved only as consultants.

Major Cost/Performance Issues

With an R value of 8.3/in., and a price of 30¢ to 40¢ a board foot, phenolic foam is the cost effective approach to insulating new construction. Flame properties are also excellent.

Possible Army Applications

Insulating is an important first step in any energy saving program. Living, office, and athletic facilities all have important heating or cooling considerations in a military installation. As fuel prices continue to rise, the relatively small capital investment of insulation is increasingly important. Phenolic foams are an excellent insulation option for new construction in Army buildings, given their high R value and relatively low cost.

High Efficiency Lighting

Technology Description

One of the most significant lighting technologies introduced in the past few years is the solid-state ballast. It performs the same function as a magnetic ballast: it starts the discharge and safely limits the current through a fluorescent lamp. The solid-state ballast operates the lamp at a high frequency (20,000 Hz), which increases the lamp's effectiveness. High frequency operation, coupled with the solid-state ballast's higher

efficiency in transferring input power to the lamp (87 vs. 79 percent for the core-coil ballast), increases system efficiency by 20 to 25 percent.

It is generally accepted that most buildings constructed in the past were excessively illuminated. Many new devices reduce input power and illumination levels proportionally. The devices described below are the latest developments in high efficiency lighting.

A phantom tube is a lamp that contains a capacitor and emits no light. It replaces one lamp in a two-lamp fluorescent ballast system. The power required is reduced by 67 percent and the light output by 75 percent. This is a significant reduction in light with a 10 percent decrease in system efficacy. The emission pattern from fixtures fitted with this device appears uneven however.

The current limiter is a device that is usually hard-wired into a two-lamp F40 fluorescent system, preferably between the ballast and the lamp. Different models reduce the light output by 20, 30 or 50 percent. At best, the power reduction is proportional to the light reduction with no loss of efficacy. Some models have the current limiter wired on the input side of the ballast. This reduces the power factor and filament voltage, which may reduce lamp life.

Specular reflectors are carefully designed, highly reflective sheets of silver or aluminum that are installed in fluorescent fixtures. Manufacturers recommend them as a retrofit in four-lamp fixtures and claim that about the same light level can be maintained by removing two lamps and installing the reflector. The reflectors tend to focus the light beneath the fixture, changing the light distribution patterns. When photometers are used to measure the total light from the systems they show that the total light output is decreased by 41 percent. Accompanied by a decrease in power use of 48 percent, this does yield a gain in fixture efficiency of 10 to 12 percent, but the installed cost of these reflectors is very high.

The energy button is a diode or a thermistor that is placed in the socket of an incandescent lamp. The diode blocks one half of the duty cycle, reducing the power to the lamp by 40 percent and the light output by 75 percent, which represents a significant reduction in efficacy. For example, a diode placed in a socket of a 100-W, 1750-lumen lamp reduces the input power to 60 W and light output to 438 lumens. Unless the cost of replacing a light bulb is a major consideration, using a 40-W, 480-lumen bulb would be more cost effective. A new bulb on the market uses a diode inside the glass envelope. Its characteristics are the same as those of a lamp with a diode in the socket. The thermistor is a similar device that reduces the initial surge of current and slowly heats up. It operates the lamp at a slightly lower than normal voltage, but this also makes the lamp operate with a lower efficacy. These devices do approximately double bulb life by reducing the initial power surge.

Sensors can be used to turn lights on when a person enters the room. Personnel sensors detect the presence of motion in a space by ultrasonic, infrared, optical, or audio techniques. If a person enters a room or space the sensor activates a relay to turn lights on. When the space is vacated, after a short period (4 to 10 minutes) the lights will be switched off. These systems are relatively expensive and operate most effectively in a one- or two-person space. However, in a one-person area the device will control only a small amount of power - 100 or 200 W of lighting. In order to be cost effective the space must be vacant a considerable portion of the day. These devices are particularly effective in spaces that are used only occasionally.

Technology Status/Commercial Availability

Energy efficient ballasts are available from a variety of suppliers for retrofit applications, while many companies offer them as options on new lighting fixtures. With a cost 10 to 25 percent higher than a coil and core ballast, the solid-state units are only beginning to be accepted as a high efficiency alternative. Specular reflectors represent a controversial and competitive market. A carefully designed reflector will allow a 50 percent decrease in lamps while showing no decrease in intensity at critical areas. A poorly designed reflection system removes half of an area's lighting fixtures and 75 percent of its light. Two kinds of reflectors are currently available: silver and anodized aluminum. Phantom tubes, current limiters, and energy buttons offer a solution where excessive illumination is present and a decrease in intensity is not a problem. They all offer a decrease in energy consumption with a corresponding decrease in lighting. Energy buttons in particular show a considerable drop in efficiency. Dimmers, lighting controllers, and personnel sensors are all applicable on a small scale or on a system basis. Lighting controllers can be custom designed for up to 1,000 channels (Powerline Communications, Inc.). These systems use microprocessors to control a variety of lighting functions while allowing wall switch and touch-tone override.

Metal halide and high and low pressure sodium lights are highly efficient, but offer bad color rendering, flickering, or other qualities that may make them poor choices for Army applications. In the intermediate term (3 to 6 years) it is expected that high intensity discharge lamps will be commercially available. In the meantime, improvements in fluorescent lights seems to be the industry's short term concern. All the technologies discussed are currently available, or will be available in the near term (next 3 to 5 years).

Development Programs/Funding Organizations

DOE, with Lawrence Berkeley Laboratory, has played a major role in the development of high efficiency lighting. Because of the large retrofit market and prospect of quick returns on investments, there are several corporations in the lighting development field. General Electric (GE) and GTE/Sylvania are active in all areas of development, while smaller companies specialize in one or two technologies. XO Industries and Luminoptics have large development programs in ballasts; while Omega Energy and Alcoa fund large programs developing reflectors; Westinghouse, Powerline Communications, and Functional Devices, Inc. continue to research complete lighting control systems.

Major Cost/Performance Issues

Electronic ballasts save energy over coil and core units, but more importantly, they create a potential for more important energy saving functions such as dimming. The $15 to $75 cost of an electrical ballast retrofit can be recouped in 1 to 3 years, assuming 24-hour use. With a dimming function added, this payback time can be reduced significantly. Removing lamps and using reflectors will net a 50 percent reduction in energy consumption but almost a 75 percent reduction in light. Efficiency can be increased by using reflectors, but at $25 to $30 per installation. Energy buttons are inexpensive, but like removing lamps result in a large loss of efficacy. The price of the buttons is often better spent on less powerful bulbs, if that is an option. Current limiters are currently too expensive unless the cost of changing fixtures is prohibitive. Light control systems can be custom designed for specific applications. Depending on the application, there can be considerable savings and an extremely short (6 months) payback time. Performance characteristics of various lighting sources are identified in Table 26.

Table 26

Performance Characteristics of Light Sources

Characteristic	Light Source					
	Incan-descent	Mercury Vapor	Fluor-escent	Metal Halide	High Pressure Sodium	Low Pressure Sodium
Efficacy	Very Low	Low	Medium	Medium	High	Very High
Intensity	Medium	High	Low	High	High	Low
Color Temperature	Low	High	Low-High	Low-High	Low	Low
Color Rendering	Excellent	Medium	Poor-Good	Good-Ex.	Poor	Very Poor
Glare	Medium	High	Low	High	High	Low
Source Geometry	Point	Point	Diffuse	Point	Point	Diffuse
Dimmability	Very Good	Good	Very Good	Good	Good	Good

Possible Army Applications

Lighting loads are particularly high in Army facilities (on a percentage basis) since air-conditioning and other electric loads tend to be relatively lower. The standardization of high efficiency lighting should be particularly attractive to Army facilities.

Smart House/Building Technology

Technology Description

The Smart House/Building Technology* is a revolutionary, single-cable wiring system for the distribution and control of energy, communications, and audio/video signals in homes and small buildings. It will be an integrated network that connects a complete line of compatible "Smart" products. In this technology, telephones, stereo

*Smart House Development Venture, sponsored by National Association of Home Builders (NAHB) Research Foundation and numerous companies.

speakers, TVs, computer terminals and an assortment of both gas and electric appliances can be plugged in anywhere in a building and controlled from anywhere inside or outside the building by integrated microelectronics and power semiconductors. The Smart chips that will be incorporated in appliances will allow them to communicate. In addition to offering added convenience, comfort control, and safety, the Smart House/Buildings will be largely programmable. This could increase energy savings by taking advantage of lower time-of-day rates.

The Smart House has a closed-loop system that requires a device or appliance to generate a signal before receiving power. That signal tells a system controller what kind of device it is (radio, power drill, etc.). The system controller (which includes new chips under development by Smart House) then sends the appropriate power through the circuit to the device. If the circuit wiring or outlet is faulty, if the device malfunctions, or if the cord is frayed, the controller will receive a different signal and shut down power. The Smart House technology can use either centralized or distributed control. Power and signal information are the data the controller uses to allow for interaction of appliances. Many system appliances will also be able to operate on lower voltage DC power. Typically, the main panel will feed both 120 volts and 48 volts power to network boxes in each room.

Technology Status/Commercial Availability

The first Smart House/Building is not expected to be commercially available until 1989. The National Association of Home Builders (NAHB) are planning to build two laboratory houses at the NAHB Research Home Park in Bowie, MD. The two houses--one gas oriented, and the other electric oriented-- will be used for preliminary design and testing of Smart House/Building products. Both GRI and EPRI will be involved with this laboratory house effort. Prototype houses will also be built to test operating features in 15 to 20 North American locations by 1988. It is expected that by early 1990 there will be 100 demonstration houses incorporating the developed Smart House/Building network hardware, software, and compatible appliances and devices. A projected timetable for Smart House installations is shown in Table 27.

Development Programs/Funding Organizations

The Smart House Developmental Venture is a project of the NAHB Research Foundation. There are a wide variety of industry groups participating in the Smart House Venture (Table 28). Their areas of involvement are also shown in the table.

Major Cost/Performance Issues

The first production models of the Smart House are expected to cost about $1,500 to $2,000 more than a typical $100,000 new home/building. After 4 or 5 years into production (late 1990s), the cost of a Smart House/Building will equal that of a conventional home/building. Although there is an initial price premium, there are advantages and other cost savings that make the system beneficial: utility rebates for load management, savings from reducing peak load demand charges, reduced fire hazards, and--for Army applications--the advantage of having a centralized control capability.

Possible Army Applications

The Smart House/Building technology has many potential applications and benefits for Army facilities, especially living quarters, administration buildings, health facilities,

Table 27

Projected Smart House Installations

	Year 1	Year 2	1989 Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
UNITED STATES										
Installation Projections:										
Single and 204 units	0	0	100	90,000	190,000	310,000	450,000	605,000	760,000	900,000
Five or more units	0	0	0	4,000	15,000	40,000	100,000	180,000	240,000	300,000
Commercial (20,000 sq ft/unit)	0	0	0	1,000	3,000	6,000	9,000	12,000	15,000	19,000
Manufactured housing	0	0	0	0	5,000	15,000	30,000	50,000	80,000	115,000
Retrofit:										
Rewire	0	0	0	3,000	8,000	19,000	36,000	53,000	69,000	84,000
Other retrofit	0	0	0	25,000	80,000	190,000	310,000	490,000	715,000	980,000
CANADA										
Installation Projections:										
Single and 2-4 units	0	0	0	3,000	9,000	18,000	28,000	40,000	53,000	67,000
Five or more units	0	0	0	1,000	2,000	5,000	10,000	19,000	32,000	47,000
Commercial (20,000 sq ft/unit)	0	0	0	0	0	1,000	1,000	1,000	2,000	2,000
Manufactured housing	0	0	0	0	0	0	1,000	1,000	1,000	2,000
Retrofit:										
Rewire	0	0	0	0	1,000	2,000	3,000	4,000	5,000	6,000
Other retrofit	0	0	0	0	3,000	7,000	15,000	28,000	47,000	70,000
OTHER COUNTRIES										
Installation Projections:										
Single and 2-4 units	0	0	0	0	0	1,000	3,000	20,000	80,000	160,000

Table 28

Smart House Industry Participants

Steering Committee

AMP, Inc.
Apple Computer
Arco Solar, Inc.
AT&T Technologies, Inc.
Bell Northern Research
Brintec Corp.
Broan Manufacturing Company Inc.
Burndy Corp.
Carrier Corp.
Challenger Electrical Equipment Corp.
Dukane Corp.
DuPont Connector Systems
Emerson Electric Co.
General Electric Co.
Honeywell Corp.
I-T-E Electric Products
Kohler Co.
Landis & Gyr Metyering, Inc.
Lennox Industries Inc.
National SemiconductorCorp.
North American Philips
Northern Telecon
NuTone Division--Scovill, Inc.
Onan Corp.
Pass & Seymour Inc.
Robertshaw Controls Co.
Schlage Look Co.
Scott Instruments Corp.
Shell Development Co.
Signetics Corp.
Slater Electric
Sola Electric
Solavoit International
Southwire Co.
Square D Co.
Systems Control, Inc.
Whirlpool Corp.
Wiremold Co.

Advisory Council Members

Agip Petroli
Bell Canada
Bell Communications Research
Copper Development Association
Department of Commerce
Electric Power Research Institute
Gas Research Institute
Ontario Hydro
Potomac Electric Power Co.
Professional Builder Magazine
Southern California Edison Co.

Proposed Product Responsibilities

Core System

Electric load center
Challenger
ITE
Square D
Circuitbreakers
Challenger
ITE
Square D
Pass & Seymour
Ground fault circuit interrupters
Challenger
Square D
Pass & Seymour
DC Power conversion and uninterruptible power source
Solar Electric
Square D
Cable
BRintec
AMP
Southwire
Connectors
AMP
Burndy
DuPont

Source: *Professional Builder*, December 1986.

Table 28 (Cont'd)

Proposed Product Responsibilities (Cont'd)

Plugs and receptacles
Pass & Seymour
AMP
Burndy
DuPont
Network interface housing
Challenger
Square D
Pass & Seymour
Power block
Challenger
Square D
Emerson
Appliance controller
Square D
Pass & Seymour
Honeywell
Network communications controller
Pass & Seymour
Honeywell
Northern Telecom
Temperature and humidity sensors
Pass & Seymour
Emerson
Honeywell
Robertshaw
Environmental system control
Emerson
Honeywell
Robertshaw
Wall Switches
Challenger
Pass & Seymour
Slater
Telephone components
Northern Telecon
AT&T

Attached and Optional Components

Electric meter
Landis & Gyr

Photovoltaics
Arco Solar
Auxiliary generator
Onan
Transfer switch
Challenger
ITE
Square D
Wire management hardware
Burndy
Wiremold
Appliance interface
Emerson Electric
Robertshaw
Appliance adapter
Pass & Seymour
Slater
Robertshaw
Occupancy sensors
Pass & Seymour
Honeywell
NuTone
Security components
Honeywell
NuTone
Smoke sensors
Pass & Seymour
Indoor air quality sensors
Pass & Seymour
Robertshaw
Door locking control
Schlage
Control panel
Honeywell
Apple
Systems Control
Voice recognition & synthesis
Scott Instruments
CATV components
North American Phillips
HVAC equipment
Carrier
Lennox
Water heater

Plumbing control
Kohler

Table 28 (Cont'd)

Attached and Optional Components (Cont'd)
Ventilation equipment
Emerson
Robertshaw
Broan
Large appliances
Whirlpool
General Electric
Lighting equipment
NuTone
North American Philips
Intercom equipment
Northern Telecon
NuTone
Entertainment products
North American Philips
General Electric
Home computer
Apple
Doorbell
NuTone

barracks, entertainment buildings and dining facilities. The potential for centralized energy control offers many potential benefits to the Army. Unlike the civilian buildings, Army facilities are operated by a central group. Smart House/Building technology offers the flexibility for centralized load management (significantly reducing utility demand charges), remote diagnostics, remote metering, and load disconnect under emergency conditions.

Secondary Batteries

Technology Description

A battery is a device that converts the chemical energy contained in its active materials directly into electrical energy by means of an electrochemical oxidation-reduction (redox) reaction. Reactions of this type involve the transfer of electrons from

one material (electrode) to another through an (external) electrical circuit. Within the battery itself ions travel through a conductive electrolyte which is usually a liquid material, but may also be a solid.

Although the term "battery" is commonly used to describe these devices, the basic electrochemical unit is referred to as a cell. The assembly of two or more cells establishes a battery.

There are two broad classes of batteries:

- Primary or "throw-away" batteries. These cells are generally used until their internal chemical energy is exhausted and then are discarded. The familiar dry cell and the popular alkaline cell are examples of primary cells.

- Secondary or rechargeable batteries, also called storage batteries. Secondary batteries offer the significant advantage that they can be recharged electrically to their original condition by passing current through them in the direction opposite to that of the discharge current. Under these circumstances, a large percentage of the energy-producing active materials are restored to their original condition.

A well-known example of a secondary battery is the common lead-acid battery used in SLI (starting, lighting, ignition) applications, particularly in automobiles. In the United States, over 70 million of these batteries were manufactured in 1986.

Secondary batteries are potentially capable of a large number of charge-discharge cycles. Accordingly, secondary batteries can be used as a means of storage of electrical energy, regardless of the means of generating the primary energy (e.g., coal, solar, wind nuclear, etc.). In general, secondary batteries are characterized (especially as compared to most primary battery technologies) by

- High power density and discharge rate

- Flat discharge curves

- Good low-temperature performance.

Technology Status/Commercial Availability

Rechargeable batteries generally have a lower energy density than primary batteries of the same size. Their charge retention is usually poorer than most primary batteries, although the capacity that is lost on standing can be restored by charging.

Energy conservation and/or load management applications of batteries at Army facilities will necessarily involve the use of secondary batteries. Therefore, the following discussion is limited to this technology area.

Throughout the technical literature, there are a great many classifications that have been used to categorize the dozens of "new" battery technologies that are being developed. For example, it is possible to classify these batteries by technology, by type of electrolyte, by negative (or positive) electrode material, or by temperature of operation. The best system of classification will be determined by the purpose of the

analysis. For example, the most useful segmentation for load-leveling applications might be:

- Commercialized systems
- Near-term (battery scale)
- Advanced development (cells and prototypes)
- Laboratory-documented.

At present, the only secondary cells which are commercially developed are:

- Nickel-cadmium
- Sealed lead-acid
- Silver-zinc
- Silver-cadmium.

Due to the high cost of silver, the silver battery systems have been restricted to a limited number of military applications, despite their very high energy density.

In addition, there are two other types of battery systems under development:

Metal-air systems, which are actually hybrids between batteries and fuel cells. Examples of these technologies are the Al-air, the Zn-air and the Fe-air systems.

Redox electrolyte systems, for example, the Fe-Cr system.

The diversity of battery systems being developed arises because no commercially available systems are yet able to satisfy the critical performance requirements for load-leveling applications. Some systems under development offer potential for tremendous improvements in energy density or power density, while others offer prospects of improvement in reaching cost objectives.

Table 29 summarizes the development status of several rechargeable battery technologies which are of potential interest for load-leveling applications. Major manufacturers of batteries are listed in Table 30 and 31.

Development Programs/Funding Organizations

Battery technology is a major component of the DOE's program to promote energy self-sufficiency and to maintain and develop a leadership position in energy technology. For many years, the DOE has provided a high level of support to battery technology development for use in electric vehicles. Programs have involved scale-up of technologies, development of cell prototypes, engineering and development of cell components and fundamental investigations of various technical challenges in several existing and new systems.

In addition, the electric utilities and EPRI have targeted batteries as a critical technology area and have provided substantial levels of support to battery development programs. Their FY87 budget for batteries totaled $3.1 million. EPRI's interest centers

Table 29

Status of Rechargeable Battery Technology

System	Advantages	Status	Challenges
Advanced Lead Acid	• Low cost • Proven performance	• Commercially available	• Deep discharge cycle life
Nickel-Zinc	• Potential low cost • High energy density	• Limited commercial availability	• Sealing of cells • *Reducing cost*
Nickel-Iron	• Proven performance • Potential low cost	• Limited commercial availability	• Increase efficiency • High rate of self-discharge • Emits hydrogen during discharge
Zinc-Bromine	• Low cost	• Advanced development	• Material durability • Stack sealing • Battery efficiency
Sodium-Sulfur	• Performance • High efficiency	• Advanced development	• Cell production costs • Electrolyte durability • Freeze/thaw survivability • Thermal management
Molten Salt Lithium-Iron Sulfide	• High energy density • Low cost	• Advanced development	• Several severe materials problems • Thermal management

Table 30

Major Manufacturers of Rechargeable Batteries (Commercialized Systems)

Manufacturer	Battery Type
Johnson Controls	Lead-acid; sealed lead-acid
Exide	Lead-acid
GNB (Gould)	Lead-acid
C&D Batteries	Lead-acid
GM Delco Remy	Lead-acid
General Battery	Lead-acid
Chloride	Lead-acid
Gates	Sealed lead-acid
Gates	Nickel-hydrogen
Gates	Nickel-cadmium
Eagle-Picher Industries	Nickel-cadmium
Eagle-Picher Industries	Nickel-hydrogen
Yardney	Nickel-hydrogen
Yardney	Silver-zinc
Yardney	Silver-cadmium
SAFT America	Nickel-cadmium

Table 31

Organizations Developing Advanced Secondary Battery Systems

Advanced Lead-Acid	**Nickel-Hydrogen**
Johnson Controls Exide C&D Batteries	Eagle-Picher Johnson Controls Gates Yardney Energy Research Corp.
Nickel-Zinc	**Sodium-Sulfur**
GM Delco Remy Exide Energy Research Corp. Yardney Eagle-Picher	Ford Aerospace Chloride Silent Power Dow Chemical
Nickel-Iron	**Zinc-Bromine**
Eagle-Picher Westinghouse NIFE	Energy Research Corp. Gould Johnson Controls
Zinc-Chlorine	
Energy Development Associates (G&W)	

on the use of batteries as load-leveling devices and small-size additions to the electric grid. In recent years, EPRI's support has focused on the development of large prototypes of batteries that can be demonstrated in load-leveling applications. Battery test programs have involved the development and testing of a 500 kWh and a 1 MWh battery based on lead-acid technology and a 500 kWh (100 kW) battery based on the Zn-$C1_2$ technology. These systems were evaluated by Public Service & Gas Company at the Battery Energy Storage Test (BEST) facility that it operated for DOE and EPRI.

A great deal of expertise in electrochemistry and electrochemical engineering is required to address the performance requirements of large-scale battery systems. Substantial capital resources can also be required.

In the last few years, the Japanese government has supported major development efforts of several battery technologies through the Moonlight programs of NEDA.

Major Cost/Performance Issues

There are several performance requirements for batteries for use in load-leveling applications. Key performance areas, summarized in Table 32, include cost (generally represented as \$/kWh), efficiency, energy density, power density, and cyclability.

Also, current trends for utility rate structures to increase demand charges and offer favorable night time rates could accelerate the use of batteries as a demand management tool.

The high cost of batteries for load-leveling applications has been a major barrier to their widespread use. In areas with high demand charges batteries may be more cost competitive, but reductions in first cost must take place before this technology can be used as a load-leveling tool at Army bases.

Table 32

Proposed Battery Requirements for Electric Utility Applications

	Peaking Duty	Intermediate Duty
Average Power	5 - 10 MW	5 - 10 MW
Peak Power	10 - 20 MW	10 - 20 MW
Typical installation size, MWh	50-200	50-200
Battery voltage, V	1000-2000	1000-2000
Daily duty cycle, h		
Discharge	5	0
Charge	5-7	5-7
Energy efficiency (round trip), %	>70	>80
Cycle life	> 1500 (10-yr minimum)	> 2500 (10-yr minimum)
Battery footprint, kWh/m^2	> 1 > 1	
Initial battery cost, \$/kWh	100 100	
Environmental impact	minimal	minimal

Possible Army Applications

The successful development of improved batteries could significantly impact energy systems at Army facilities. Several of the probable uses of such battery systems are identified below:

- Integration of batteries with onsite power systems (district heating, cogeneration, base power systems) to reduce peak demands and manage electric use. This would
  - Reduce the capacity and capital costs of onsite power systems
  - Provide better matching of electric and thermal outputs (for example, with district heating systems).
  - Operate onsite power systems under steadier loads, leading to higher efficiency.
- In conjunction with renewable energy resources (PV, wind) so system output can be better controlled to match loads, or to increment power generation capabilities in a modular fashion based on demand, or to supply remote locations.

Daylighting Technologies

Technology Description

Many materials and technologies are being developed to improve both core and perimeter lighting. Major research falls in these areas: (1) optical switching materials that control the quantity of light and heat transmitted or rejected from a building, and (2) light guides for core daylighting. Advances in these areas will help to reduce lighting and cooling equipment, decrease energy use and utility demand charges, and improve comfort conditions. Advanced glazing materials such as electrochromics, thermochromics and photochromics are now being researched for dynamic control of glazing transmittance. Low emissivity coatings combined with gases and gels between panes are also being researched for their improved R factors.

Technology Status/Commercial Availability

Conventional glazing materials operate with static transmittance and provide a poor balance between daylighting and reduced cooling demands. Constant light transmittance of current glazing materials ranges from 8 to 90 percent. The DOE goal is to have controllable and variable transmittance ranging from 10 to 70 percent. The primary activity of DOE and industry is electrochromic materials and devices. Electrochromics change their emissivity and color in response to an electrical signal. Materials coatings receiving the most attention are metal oxides such as nickel and tungsten. Japan is ahead of the United States in this research, but as shown in Table 33, there are a variety of U.S. companies researching the technology. Research has been going on for 3 to 4 years. The electrochromics coatings are expected to be commercially available after 5 years (1992).

Photochromics (light sensitive coatings) are well developed, but expensive. Interest in these materials is currently less than in electrochromics. Thermochromics (heat sensitive coatings) are not a proven technology. These materials do not offer as much

Table 33

Daylighting Technology Companies

Electrochromics

- PPG
- Ford Glass
- Asahi Glass (Japan)
- EIC Corporation
- Tufts University
- LBL, SERI
- Major automotive manufacturers (GM, Nissan, Toyota, Mazda)

Photochromics

- Corning Glass
- American Optical
- Major automotive manufacturers
- LBL, SERI

Thermochromics

- Honeywell
- LBL

Light Pipes

- Japanese fiber optic companies
- TIR Systems (Canada)

Low Emissivity Windows With Gases and Gels

- Interpane Windows
- Marvin Windows

versatility and control, and are therefore not receiving much R&D activity; however, this technology should still be available commercially in 5 years.

Light pipes, which funnel light to the core of buildings, are commercially available in Japan, but are extremely expensive. There is tremendous potential for this technology if the costs can be reduced. A Canadian firm, TIR Systems, has begun a demonstration program for the advancement of this technology.

Recently there has also been a great deal of activity using low emissivity coatings combined with gases and gels between window panes. Low E windows combined with gases such as argon and kryston provide an R value of 4 (most glass in windows presently have an R value of 2). Higher cost is the major barrier to their commercial availability. See-through materials such as Aerogel or gas mixes combined with triple glazings are expected to achieve R values of 8 to 10 within the next 5 years.

Development Programs/Funding Organizations

There is a significant amount of activity for improved daylighting technologies within the public and private sector. The major participants are listed in Table 33. The DOE, through LBL and SERI, is the primary government organization sponsoring R&D in this area. These are some of their major activities:

Highly Insulating Window System. LBL recently field tested a 3 ft x 3 ft prototype of an R7 glazing. LBL computer simulations suggest that these windows should perform better than an insulated wall over the heating season on any orientation in cold northern climates. Additional development of better frames to accept the high-R glazing is also needed.

Smart Windows. These have controllable optical properties so that visible light and solar transmission can be dynamically controlled to minimize cooling loads, maximize daylight benefits and reduce peak electric demand. Several different types of optical coatings for glass are being studied that might perform these functions. Motorized controls on blinds and shades can also provide similar performance functions today.

Low Emissivity Coatings. Industry predicts that over 25 percent of all residential windows will have low E coatings by 1990 (R3 to R5). There are many types of coatings and window design; but little agreement on how to specify them, or how to best use them on different orientations in different climates. Programs to guide the specification and use of these products should be further developed.

Field Testing. LBL has developed a unique field test facility, the Mobile Window Thermal Test (MoWiTT) facility designed to accurately measure window performance in the field. It is a very sophisticated facility that can be used to validate simulation models, test new technology, etc.

Improved Solar Heat Gain. Accurate prediction of cooling loads is critical to sizing equipment and for thermal comfort; it requires good solar heat gain models for all of the sun control and shading devices that are commonly used. Unfortunately, accurate data are virtually nonexistent. ASHRAE and DOE are seeking a third party to cofund a 2-year project to develop a new solar heat gain methodology.

Simulation Models/Design Tools. LBL is developing easy-to-use but accurate design tools, based on state-of-the-art computer models. Cosupport of these activities is needed to provide useful tools for architects and engineers in a relatively short time frame.

Major Cost/Performance Issues

The major issue affecting light guides, low E windows combined with gases and gels, and photochromics is cost. These systems are currently too costly for commercial applications. Optical switching in windows also must address problems of basic switching mechanisms (electrochromics) and material degradation.

Advances are still needed in two major areas: better use of existing technology options and development of the next generation of advanced optical materials and systems. Improved window performance would potentially reduce high demand charges at Army bases in addition to providing improved thermal and visual comfort.

Possible Army Applications

Advances in glazing materials and light guides could significantly impact the thermal loads and visibility of all types of Army buildings. Improved windows can be installed in all new construction or used to retrofit buildings that need better thermal and visual load control.

Despite the advances made in window design and performance characterization over the last decade, there are significant remaining opportunities to further improve window performance in buildings. Windows still account for about 20 to 25 percent of total energy use in buildings, influence lighting energy needs, have a large effect on peak demand, and have a major impact on thermal and visual comfort, and therefore productivity. Most Army buildings could benefit directly from these advances, in terms of both energy dollars saved and improved comfort/productivity.

8 CONCLUSIONS AND RECOMMENDATIONS

This report has reviewed many technologies for HVAC, onsite power, industrial systems, and renewable energy. The section for each technology included a description, a review of the development or commercial activities involving it, a discussion of cost and performance, and suggestions for applications in Army facilities.

It is recommended that this report be used as a reference by CENET members and other persons at all levels who perform and manage energy technology research.

METRIC CONVERSION FACTORS

°F	=	(°C x 1.8) + 32
°C	=	(°F - 32) x 0.55
1 ton	=	16,000 Btu (cooling capacity)
1 ft	=	0.3048 m
Btu	=	1.055 kJ
Kelvin	=	°C + 273.15
°C	=	Kelvin - 273.15
mph	=	1.609 km/h
in.	=	2.54 cm
1 psi	=	6.894 kPa
1 lb	=	0.4536 kg
1 micron	=	1×10^{-6} m

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ACRONYMS

AC	alternating current
AFBC	atmospheric fluidized bed combustion
ARI	Air Conditioning and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BEST	Battery Energy Storage Test (facility)
CENET	Corps of Engineers National Energy Team
CFBC	circulating fluidized bed combustion
CFC	carbonate fuel cells
COE	coefficient of energy
COP	coefficient of performance
CSPF	cooling seasonal performance factor
DC	direct current
DOE	U.S. Department of Energy
EER	energy efficiency ratio
EPRI	Electric Power Research Institute
FBC	fluidized bed combustion
FEAP	Facilities Engineering Applications Program
GE	General Electric
GHP	gas-fired heat pump
GRI	Gas Research Institute
GTE	General Telephone and Electric
HAWT	horizontal-axis wind turbine
HHV	high heat value
hp	horsepower

HSPF	heating seasonal performance factor
HVAC	heating, ventilating, and air-conditioning
IC	internal combustion
IEA	International Energy Agency
IFC	International Fuel Cells
IGCC	integrated coal gasification combined cycle
IGT	Institute of Gas Technology
LBL	Lawrence Berkeley Laboratory
METC	Morgantown Energy Technology Center
MoWiTT	Mobile Window Thermal Test
NAHB	National Association of Home Builders
NBS	National Bureau of Standards
NEDA	National Electronic Distributors Association
NYSERDA	New York State Energy Research and Development Authority
O&M	operation and maintenance
PFBC	pressurized fluidized bed combustion
PV	photovoltaic
R&D	research and development
RDT&E	Research, Development, Test and Evaluation (program)
SAI	Science Applications, Inc.
SERI	Solar Energy Research Institute
SOFC	solid oxide fuel cells
SLI	starting, lighting, ignition
TA	Temperature, Ambient
VAWT	vertical-axis wind turbine
WT	wind turbine

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